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LED Lighting Technologies
Smart Technologies for Lighting Innovations

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Please see article on page 46.

Lighting Technologies

Smart Technologies for Lighting Innovations

17 Preamble

21 Keynotes

29 Lighting Business Trends

75 Lighting Technology Trends

141 Human Centric Lighting

193 LEDs, OLEDs & Laser Technologies

275 Drivers, Connected Lighting & IoT

359 Materials & Engineering in Lighting

431 Technologies in Applications

485 Lighting Quality & Testing

527 Human Centric Lighting II

543 Lighting Requirements

561 Workshops

17 Preamble

18 LpS 2018 - Proceedings
by Siegfried Luger, Luger Research e.U.

21 Keynotes

22 The Transformation of Lighting
by Dr. Guido van Tartwijk, Tridonic

24 The Lighting Industry's Journey Towards New Growth
by Rogier van der Heide

29 Lighting Business Trends

30 Strategic Roadmap of the Global Lighting Industry
by Jan Denneman, Global Lighting Association

32 EU Circular Economy Policies are Impacting Lighting Product Design and Business Models
by Ourania Georgoutsakou, LightingEurope

34 Ecodesign Directive and Energy Labelling Regulation - Short Term Consequences for Lighting Products
by Heiko Becker, ERCO

36 The Role of Governments in the Transformation of the SSL Industry
by Dr. J. Norman Bardsley, Bardsley Consulting

46 Future-Proofing Lighting Control Systems
by Patrick Durand, Future Lighting Solutions

52 Managing Connected Lighting Solutions in Real Life
by Dr. Giovanni Frezza, Molex

58 The Business Case for Sensing – How to be Ready
by Tom Griffiths, ams AG

66 Professional Lighting between Vision and Reality
by Christian Lade, Vossloh-Schwabe Deutschland GmbH

70 Horticultural LED Lighting Market, Industry and Technology Trends
by Pars Mukish, Yole Developpement

75 Lighting Technology Trends

76 Repro-light: Modularity, Sustainability & Personalization for the Lighting Industry
by Dr. Katrin Tanzer, Bartenbach GmbH

84 Zhaga: The LpS 2018 Update
by Dr. Dee Denteneer, The Zhaga Consortium

94 Lighting Goes Smart — Should We Care About Cybersecurity?
by Dipl. Math. Alexander W. Koehler, UL

102 Metameric Circadian Lighting: A Technology Analysis
by Tamara Aderneuer, CSEM Center Muttenz

108 How Digital Lighting Will Further Revolutionize Automotive Lighting
by Pierrick Boulay, Yole Développement

112 How to Solve Increasing Challenges in LED Luminaire Production
by Markus Spiekermann, BJB GmbH & Co. KG

118 Can the Success of OLED Displays be Transferred to Lighting?
by Dr. J. Norman Bardsley, Bardsley Consulting

124 Total Lighting Efficiency: Think Outside of the Chip
by Tom Veenstra, Innotec

134 The Technology and Implementation of Dynamic Beam Shaping
by David Kriebel, LensVector

141 Human Centric Lighting

142 Human Centric Lighting – Quo Vadis?
by DI Johannes Weninger, Bartenbach GmbH

148 Lighting and Emergency Department Clinician Wellness and Performance Improvement
by Octavio L. Perez, Ph.D (NOMINEE: LED professional Best Scientific Paper Award 2018), Icahn School of Medicine at Mount Sinai, Department of Population Health Science and Policy

164 A Design for Tunable LED Lighting that Reduces the Incidence of Myopia
by Dr. Stephen Mason, Sustainable Eye Health Pty

176 Implications for Human-Centric Lighting Design in Tropical Nursing Homes: A Pilot Study
by Dr. Szu-Cheng Chien (NOMINEE: LED professional Best Scientific Paper Award 2018), Singapore Institute of Technology

186 Full Spectrum LEDs and Indoor Daylight Support for Health and Wellbeing
by Octavio L. Perez, Ph.D, Icahn School of Medicine at Mount Sinai, Department of Population Health Science and Policy

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193 LEDs, OLEDs & Laser Technologies

194 Modeling and Quantifying LED Variability
by Dr. Thomas Mérelle, Pi Lighting

208 Hermetic Polymer-Free White LEDs for Harsh Environments
by Dr. Michael Kunzer (NOMINEE: LED professional Best Scientific Paper Award 2018), Fraunhofer Institute for Applied Solid State Physics

214 Heat Fluxes and Temperatures in Chip-on-Board LEDs for Different Package Structures and Phosphor Technologies
by Dipl. Phys. Max Wagner, Technische Universität Darmstadt, Laboratory of Lighting Technology

220 Advancements in LED Technology Enabling High-Luminance LEDs
by Dr. Werner Goetz, Lumileds

232 Rapid Evolution of High-Power LEDs Package from SMD to CSP to Direct Mountable Chip
by Denis Xavier, NICHIA Europe B.V.

238 New Human-Centric Lighting Based on TRI-R Spectrum Technology
by Kumpei Kobayashi, Toshiba Materials

244 LED Filaments – A new Technology Enables Classical Design in LED Retrofit Lamps
by DI Markus Hofmann, OSRAM Opto Semiconductors

250 An Introduction of OLED Lighting Technology
by DI Claudia Keibler-Willner, Fraunhofer FEP

256 The Latest Developments in Laser Light Sources For Industry-Leading Luminance
by Julian A. Carey, SLD Laser

262 Linear LED Strip Based on a High Frequency Design
by Dipl. Ing. Dr. Roland Michal, BILTON International GmbH

268 Defining the Spectrum for Your Unique Lighting Application – Spectrum, TM-30-15, and Human Centric LED Sources
by Tom Jory, Luminus Devices, Inc.

275 Drivers, Connected Lighting & IoT

276 The Business Case for Connected Lighting and IoT Services Built on Top
by Thomas Moder, Tridonic

284 Benefits of an Information Centric Lighting Network
by Dr. Simon Slupik, Silvair

290 OpenAIS: Advantages of IoT Connected Lighting in Reality
by Dr. Stefan Verbrugh, Signify

300 Simulation Techniques During the Development of an LED Driver
by Antonio Cuadra Gimenez, ELT

308 Latest Development of Drivers | Control and Dimming
by Dr. Toke Meyer Andersen, Nordic Power Converters

316 Influence of Converter Topology on the System Interactions
by DI Markus Heckmann, OSRAM

326 DALI-2: Standardized, Interoperable Components and Smart Luminaires
by Dr. Scott Wade, DiiA

330 Connected Lighting Use Cases and End User Benefits: Fixture Based Control for Outdoor and Indoor Lights
by Dr. Peter Duine, Signify

334 Connected Emergency Lighting — Safety and Security in Controls and Emergency Lighting
by Jeremy Ludyjan, Fulham

338 Lighting System Based on Visible Light Communication
by Prof. Guido Piai (NOMINEE: LED professional Best Scientific Paper Award 2018), Interstate University of Applied Sciences NTB

346 Size Matters – Small Form Factors Drivers to Support Flicker-Free Airy and Artistic Luminary Design
by Keith Hopwood, Seoul Semiconductor

350 Requirements on High Performance LED Driver for Professional LED Lighting
by Ulrich vom Bauer, Infineon Technologies AG

359 Materials & Engineering in Lighting

360 How Next Generation Design Tools Accelerate Time to Market and Secure Design Decisions
by Francois Mirand, Future Lighting Solutions

364 Reinventing Office Lighting — The Making-of an Innovative Office Task Light
by Dipl. Designer Till Armbruester, Licht Kunst Licht AG

370 Injection Moulded Diffraction Gratings on Curved Surfaces. A Breakthrough for a Cost-Effective Industrial Mass-Production
by Dr. Manuel Walch, kdg opticomp GmbH

374 A New Approach to Optical Beam Shaping for Lighting Applications based on Nano-Optics
by Dr. Marek Škereň, IQ Structures s.r.o.

384 Rapid Prototyping of Complex 3D Optical Components
by Dr. Ladislav Kuna, Joanneum Research

390 Semi-Empirical Characterization of Freeform Microlens Arrays
by Dr. Oscar Fernandez (NOMINEE: LED professional Best Scientific Paper Award 2018), CSEM

396 The T-Word: Tolerancing, and its Role in Illumination Optics Design
by David Jacobsen, Lambda Research

402 Multi-Functional Optical Silicone-to-Thermoplastic Over-Molded Component for LED Lighting
by Dr. Francois de Buyl, Dow

408 Flexible Graphite for Superior Thermal Management Solutions in LED Lighting
by Jeff Gough, NeoGraf Solutions LLC

416 Aluminum Oxide PCB - Technology for Developing New Generation LED Solutions
by Dr. Aleksey Osin, RUSALOX

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422 Cost-Effective Manufacturing of High-Quality ITO Thin Films on 300 mm CMOS for Next Generation Display Technologies
by Dr. Claudiu Valentin Falub, Evatec

431 Technologies in Applications

432 The Dark Side of Light: Effects of Light Pollution on Insects and Agriculture
by Dr. Maja Grubisic, Leibniz-Institute IGB

438 LEDs Solutions for Sports Lighting
by Dr. Shih Shun Chang, Lumileds

446 Dynamic Lighting Technology
by Noe Bory, Insolight

450 Plants' Responds to Exposure of Different Lighting Conditions
by DI Volkmar Keuter, Fraunhofer-Institute for Environmental, Safety and Energy Technologies UMSICHT

456 Closed Loop Control Systems for Supplementary Lighting in Smart Greenhouses
by Dr. Viktor Zseller, ARROW Electronics EMEA

464 Universal LED Tubes: Detailed Descriptions of Design, Technologies and Market
by Dr. Martijn Dekker, Seaborough

470 Water Metering Data Acquisition and Transmission Through Street Lighting Enabled Network
by Arturo Rubio, ELT

478 Luminaire Efficiency | A Proposal to Think Different
by Andreas Niederstätter, Swareflex

485 Lighting Quality & Testing

486 How to Tackle the Increasing Complexity at Legislative Compliance
by Jacob Nuesink, DEKRA

492 Aging of Potted LED Modules in Terms of Realistic Conditions
by Thomas Schulz, LUMITRONIX

498 Reliability of New Light Quality Metrics: Challenges and Opportunities
by Dr. Benoit Hamon, Pi Lighting

506 Destroy in the Lab to Last in the Field – LED Robustness, Reliability and Life Time Testing
by DI Alexander Wilm, OSRAM Opto Semiconductors

512 Temperature Profiling of Secondary LED Optics by Infrared Thermography
by Dr. Peter W. Nolte (NOMINEE: LED professional Best Scientific Paper Award 2018), Fraunhofer Application Center for Inorganic Phosphors

518 Light Flicker: A Reasonable Measurement Method in View
by DI Peter Erwin, Der Lichtpeter

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527 Human Centric Lighting II

528 Effects of Temporally Modulated Illumination to Human Beings: Nine Statements from a Research Perspective
by DI MMag. Markus Canazei, Bartenbach

536 Miniaturization and Its Consequences
by MLL Marcel Hubeli, Bartenbach

543 Lighting Requirements

544 Spectral Innovations in Theater Lighting
by Dipl. Ing. Markus Reisinger, Bühnenplanung Walter Kottke Ingenieure GmbH

548 A Call for Innovation – Can Entertainment Lighting Requirements be Combined in a Comprehensive Lighting Solution
by Dipl.-Wirtsch.-Ing. (BA) Ing. Christian Allabauer, OETHG - Österreichische Theatertechnische Gesellschaft

554 Modern Lighting Audits - Technology Supporting Designers and Contractors to Verify Lighting Installation Quality
by Miko Przybyla, GL OPTIC

561 Workshops

562 Solid-State Lighting Measurements
by Dr. Denan Konjhodzic, Instrument Systems

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LpS 2019

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Preamble

LpS 2018 - Proceedings

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Acknowledgement

This year we will be publishing the 8th LED professional Symposium Proceedings. Behind this compendium lies a great deal of work and, more importantly, an enormous pool of knowledge about the latest developments in the field of lighting technologies.

For this reason I would like to start by thanking all the authors who have collected the most recent information from research and industry and put a lot of time and effort into these valuable contributions. Many thanks also to all our editors, graphic designers and IT experts for creating this high-quality conference proceedings.
At this point I would like to thank also our main partners of the LpS 2018 symposium, who made the event possible with their premium support. The special thanks go to: **Seoul Semiconductor**, **Future Lighting Solutions, Mouser Electronics, Osram Opto Semiconductors, Topsil Global, Tridonic and WAGO**.

Objectives

As in past years, the main focus this year is on “illuminating” the latest developments from the light source to the applications. In terms of content, we have divided LpS 2018 into six major thematic blocks: Business Trends, Technology Trends, Light Sources, Digitization, Quality Engineering and Human Centric Lighting; all of which are listed in the LpS 2018 program.

The Proceedings LpS 2018 will serve as a comprehensive reference work when it comes to delving even deeper into these key topics. Since it is not possible to attend all lectures at the conference in person, this volume also serves to provide a detailed view of all the lectures.

In regards to the Trends in Lighting Conference, which runs in parallel to the LpS every year: As of yet there have been no full-paper contributions of the TiL conference due to the fact that the TiL program is mainly about creative solutions and approaches.

However, should there be the desire to receive certain contributions as full-paper, we will gladly include this in our considerations for the coming years — e.g., as a supplement to the LpS volume.

Print vs. Digital

Last year we asked our participants whether they would rather have the proceedings in print or digital format and over 90% of them spoke out in favour of a digital version. With a volume of over 600 pages, the printed book has also become relatively cumbersome. Taking both of those facts into consideration we decided that this year’s edition will be in digital form only.

Nominees

The following authors were nominated by the jury for the best scientific contributions: Chien Szu-CHENG, Singapore Institute of Technology; Oscar FERNANDEZ, CSEM; Michael KUNZER, Fraunhofer-Institute for Applied Solid State Physics; Peter W. NOLTE, Fraunhofer Application Center for Inorganic Phosphors; Octavio PEREZ, Mount Sinai Hospital; Guido PIAI, Interstate University of Applied Sciences NTB.
The following companies were nominated by the jury for the LpS/TiL 2018 Awards: BILTON, BARTENBACH, FUTURE LIGHTING SOLUTIONS, GL OPTIC, INSOLIGHT, KHATOD, LUMITRONIX, TOSHIBA MATERIALS, SEOUL SEMICONDUCTOR, NICHIA, PHYSIONARY, SELTEKA, SILVAIR, TRIDONIC, TRILUX.

Enjoy Reading

The Luger Research e.U. team would like to wish all readers inspiration, motivation and profound insights into the world of lighting technologies and applications. Our aim is to make a small contribution to the application of high-quality lighting solutions and to provide valuable impulses for people and the environment through light.

Thank you for participating at the LpS &TiL events!

Yours Sincerely,

Siegfried Luger, Event Director
Bregenz, September 2018

PS: The Proceedings has been published with the support of **Bartenbach**, **Future Lighting Solutions** and **Seoul Semiconductor**.
PPS: The LpS 2019 and TiL 2019 will take place again next year in Bregenz from **24th to 26th September 2019**.
PPPS: **Call for Papers 2019** - You already have the opportunity to submit your lecture concept (abstract) for the LpS 2019. Take the opportunity at: **www.LpS2019.com/cfp**

PPPPS: We are also looking forward to your suggestions for improvement next year! Please write to us at **info@LpS2019.com**.

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Keynotes

22 The Transformation of Lighting
by Dr. Guido van Tartwijk, Tridonic

24 The Lighting Industry's Journey Towards New Growth
by Rogier van der Heide

The Transformation of Lighting

Dr. Guido van Tartwijk
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Abstract

Lighting has come a long way since the invention of electric light. With the arrival of the Internet of Things, the idea of remote-controlled lighting based on the human centric approach is becoming reality. The world of IT has entered the lighting industry.

We will be looking at the challenges and possibilities this will bring to the lighting industry and how different solutions can be utilised to bring about a successful transformation of the existing lighting system into a future-proof one.

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The transformation of lighting

Lighting has come a long way since the invention of electric light. New standards are being proposed at ever shorter intervals: lm/W improvements have, by and large, lost their relevance, colour rendering index values above 90 are becoming common practice, and digital dimming and controls is the next big thing. The world of IT has entered the lighting industry. What challenges and opportunities will this bring? How can different solutions support the successful transformation of the existing lighting system into a future-proof one?

HCL is a guiding principle for further developments. Owing to the lack of natural light and the abundance of artificial light, the human circadian rhythm - our internal clock - is increasingly disrupted, which affects our visual perception, health and emotions. Human centric lighting concepts therefore place people at the heart of things and aim to simulate natural daylight over the entire day. Tunable White, for example, allows users to vary the colour temperature of LED light and is a key to dynamic lighting indoors. Research projects such as Double Dynamic Lighting by innovative thought leaders aim to create a new paradigm for lighting which can contribute to better health and well-being by combining daylight and dynamic lighting technology.

The Internet of Things (IoT) opens up new technological possibilities — and light can become its backbone. The existing infrastructure for light is th ideal basis for the IoT. With the arrival of the IoT, the idea of remote-controlled lighting also starts to take the human centric approach into account.

About Guido van Tartwijk

Dr. Guido van Tartwijk, CEO of Tridonic, has more than 20 years of international experience in the semiconductor/LED electronics and lighting industry. Prior to joining Tridonic in November 2016, he was CEO of the LED electronics section at Philips Lighting and held various senior executive roles at Philips Lighting in China and the Netherlands. Before that, he worked in several highly innovative start-up companies in the Silicon Valley and Europe.

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The Lighting Industry's Journey Towards New Growth

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Abstract

The Lighting industry has got fantastic opportunities to create new value with light.

That is much needed, because none of the large, established, old-world lighting companies are demonstrating the results that their investors would like to see - and would expect afterall. Because the lighting sector is full of new technology concepts, and has many new application areas.

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The industry does not embrace the new values and the new purpose of light.

While light was always meant to illuminate, today that is only a small part of what light can do. You are familiar with the list of new applications and new values: light to make you healthy, light for productivity, light for traffic safety, light to grow food in urban farms... Light for everything! We hear this again and again. But these are not just new market opportunities that the industry can easily cater for. It is insufficient to consider the application only. These new "value spaces" for light have something in common that does not show in the market place:

They come along in a new way.

The new and exciting applications of light do not rely on light sources only, but also on the precise control of them. The meaningful application of data enabled lighting depends on deep knowledge in fields of expertise that were never covered by the lighting industry. And I don't even touch the subject of transforming lighting into "the senses of the building", making lighting the nerval sytem of the BMS.

All of my lighting friends are true experts, however none of them could tell me the exact kind of light needed to grow parsley, and how to make it. All of my lighting control colleagues are great gals and guys, but none could tell me what the system architecture is of a parking management system that gets realtime information from the luminaires. All of my designers are very experienced, but none of them could map the user experience journey for a nurse or a doctor in a hospital, providing patients with a light environment that is proven to promote recovery.

We are familiar with the benefits of light, and we topped up our knowledge in the field of melatonin, sensors, zigbee, nano-optics and human centricity. But the industry seems to underestimate that there is much more that has to be transformed. The way all these exciting new lighting solutions are being designed, developed, manufactured, installed and commissioned is rapidly forming a completely new paradigm and a new business model. It like night and day compared to how things always went. The time that we stay in our comfort zone and follow a creation process that delivers luminaires that are just a bit more efficient... Is definitely over.

Lighting solutions have changed. But the process to create success with light is changing much more.

To be competitive, successful, at the cutting edge again and to keep having fun, the lighting industry has to re-think its product creation process entirely. Purposeful lighting solutions do not come along anymore when created in solitude, made inside your company and being based on existing paradigms. What we have to create now, is so different from everything we've done in the past, that it is not sufficiently insightful to ask a lighting designer what she would like to see. It is not enough to get input from an architect or an engineer. Or to hire a famous product designer to do another signature design.

The lighting industry should not be scared to face that everything is upside down now. We've got to embrace the opportunities that come with change and organize ourselves around them, because recovery is becoming more difficult, more expensive and more painful with every day we wait.

This keynote speech introduces a new paradigm for collaboration in the development of lighting solutions. It introduces a model for the creation of new value in the 110 billion Euro lighting industry. A model that aims to understand the future, instead of building further on the past. A model of "integrative design", that recognizes the need for cross-professional collaboration, in product creation teams that include experts in connectivity, software and user experience. A model that fosters the intimate exchange between technology researchers, designers, scientists and commercial experts, and that moreover explicitly includes application professionals who are on the demand side themselves: facility managers, healthcare providers, traffic modelers, retail marketers...

The lighting industry badly needs new customer insights.

This is the “next level of the game”, and the key drivers of the product creation process are creative empowerment, interaction, profound customer insights, and - which is perhaps the only thing that has not changed - our responsibility to deliver great lighting. Because just like clean air and potable water, good light is a life-critical environmental factor, and a fundamental right of every human on this planet.

Trends in Lighting aims to become the global platform for integrative design of purposeful lighting solutions. The conference wants to inspire designers, manufacturers, technologists and end users to capture new opportunities together. This keynote provides a guiding framework for the conference, and encourages you to connect with the other attendees and speakers, find new value spaces for the lighting industry, and discover how to enter these with purposeful, future-oriented lighting solutions.

Figure 1: Lighting design for Seoul’s massive Sky Garden, created on an abandoned motorway that crosses the city (2017).

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Lighting Business Trends

30 Strategic Roadmap of the Global Lighting Industry
by Jan Denneman, Global Lighting Association

32 EU Circular Economy Policies are Impacting Lighting Product Design and Business Models
by Ourania Georgoutsakou, LightingEurope

34 Ecodesign Directive and Energy Labelling Regulation - Short Term Consequences for Lighting Products
by Heiko Becker, ERCO

36 The Role of Governments in the Transformation of the SSL Industry
by Dr. J. Norman Bardsley, Bardsley Consulting

46 Future-Proofing Lighting Control Systems
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52 Managing Connected Lighting Solutions in Real Life
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58 The Business Case for Sensing – How to be Ready
by Tom Griffiths, ams AG

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70 Horticultural LED Lighting Market, Industry and Technology Trends
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Strategic Roadmap of the Global Lighting Industry

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Foreword

An important role of the **Global Lighting Association** [1] is to share knowledge on global trends, and for this reason we have prepared The Strategic Roadmap of the Global Lighting Industry. The Association also initiates policies and actions in areas of common interest and provides governments with relevant product and market information

The disruptive technology inventions of LEDs and intelligent lighting systems bring advantages to many stakeholders in the value chains of lighting, building management, city management, data and IoT industries. The lighting industry will ensure that people benefit from these inventions through better quality, energy efficient lighting that is smartly tuned to their changing needs and activities.

Summary

In recent decades the world has seen enormous changes in lighting.

The industry has witnessed **two highly disruptive technology developments**. Light emitting diodes (**LEDs**) from quality producers have developed to a level of performance and light quality to enable the rapid replacement of most conventional light sources. Secondly, LEDs have been integrated into **intelligent lighting systems**, making them capable of full integration with the digital world. Consequently the industry is now moving towards system solutions, in addition to better lighting quality than that previously offered by traditional technology.

A 3rd photo-receptor in the human eye has been discovered, providing scientific evidence that light not only enables vision, but also impacts performance and feelings of well-being. This enables lighting to add value to society from sustainability to quality of light.

The world has many challenges, and some are very relevant to the lighting industry. These include the challenges posed by **globalization, climate and demographic changes**.

The challenges confronted by the lighting industry are **digitalization, new applications of intelligent lighting systems** and the increasing demand for **buildings supporting human health, well-being and productivity**. Hence the value of lighting is moving from energy efficiency to the wider spectrum of quality of life and improved well-being.

This transition requires **new paradigms for all stakeholders** — the industry, customers and users and particularly governments and regulators, who need to view the capabilities and benefits of lighting within this wider context.

References

[1] www.globallightingassociation.org

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EU Circular Economy Policies are Impacting Lighting Product Design and Business Models

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The EU is driving change to achieve its vision for a Circular Economy through a combination of strategies and regulations that address a product's entire life cycle.

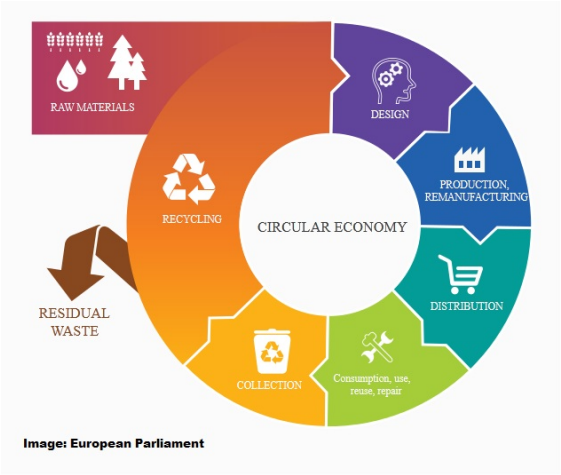

Figure 1: Circular Economy

New requirements are emerging addressing such diverse issues as the quality and variety of the plastics used in a product, increased information requirements on the chemical substances and critical raw materials it contains, making products easier to repair and upgrade and requiring removable and replaceable components.

Incentives for industry and consumers to opt for more circular products include the introduction of a reparability score and new labels, and discussions to render 'non-circular' products more expensive, for example via the eco-modulation of WEEE fees.

All these developments have a direct impact on product design and business models.

LightingEurope, the industry association representing the lighting industry in Europe, is working with members to apply 'circular thinking' to lighting products. We view the circular economy as an opportunity for growth for the industry: with the transition to LED technology and the introduction of additional devices and functionalities within the lighting system, circular thinking will enable sustainable products and new business models.

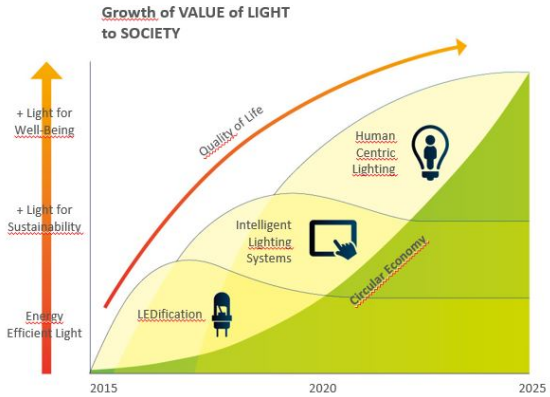

Figure 2: Strategic Roadmap

LightingEurope is liaising with rule makers in the EU to educate them about the diversity of lighting products and applications, arguing that there is no 'one-size-fits-all' approach when it comes to circular lighting products as they have to address diverse application specifications and norms as well as different customer expectations.

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Our most recent engagement is in the area of EU ecodesign, a set of rules that originally focused on increasing energy efficiency, but that has now become the main tool to deliver the EU's circular economy strategy. Draft texts for the next set of ecodesign rules for light sources introduce mandatory removability and reparability requirements to be introduced as soon as 2021.

At the same time, we continue to shape an industry-wide consensus on how to apply the Circular Economy to lighting products. The LightingEurope 2017 White Paper on Serviceable Luminaires in a Circular Economy focuses on the serviceability of luminaires and explores the business models and growth opportunities around reparability, maintenance, replaceability and upgradability. A voluntary scheme to provide information about the serviceability of luminaires according to their design characteristics is discussed in order to provide the market with information on the additional capabilities of luminaires.

LightingEurope is now working on a new publication to explore and provide guidance on the technical, economic and legal parameters that need to be in place to support the higher penetration of serviceable luminaires, looking at warranties, product lifetime, access to spare parts, repair networks and liability. We are also exploring the business potential of serviceable luminaires with a market study by an independent third party expected by the end of 2018.

Ecodesign Directive and Energy Labelling Regulation - Short Term Consequences for Lighting Products

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New ecodesign and labelling requirements are currently under discussion and they will introduce significant new requirements for the lighting industry, including the phase out of conventional technologies, increased performance requirements and new obligations for 'circular' products.

LightingEurope, the industry association representing the lighting industry in Europe, is working with the European Commission and national authorities to shape these new rules. Our objective is to agree on simple and robust rules that are easy to interpret, apply and enforce.

Herewith an overview of some key messages LightingEurope has been voicing.

Realistic timetable in Ecodesign and RoHS

Markets need sufficient time to understand and evaluate alternative lighting products and to adjust their budgets and replacement cycles. LightingEurope has teamed up with another 17 industry associations and has issued a joint statement asking for a realistic transition timetable to substitute lighting technologies and products.

A premature phase-out may lead to technical issues and unnecessary waste and costs. Users may respond by stockpiling the old technology, which will neutralise the desired energy and environmental savings.

Where there are no substitute products and technologies, regulators must continue to allow special purpose products on the EU market by exempting them from the Eco-design rules and renewing the exemptions under RoHS.

Removability requirements in Ecodesign legislation

The focus of ecodesign rules is shifting away from strictly addressing energy performance to now also acting as a tool to promote the implementation of the EU circular economy ambitions.

Recent drafts for ecodesign and labelling rules propose a mandatory requirement for removable light sources separate control gear, applicable to all lighting products and all lighting applications. Complying with this new requirement would necessitate a redesign of luminaires by 1 September 2021.

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LightingEurope believes a realistic timeline is indispensable to adapt business models and products. Some aspects of removability are possible today, but others will take more time. We propose information requirements for removability to address the needs of market surveillance authorities and recycling facilities. A detailed Impact Assessment should take place to assess how to apply any further circularity requirements to diverse lighting products and applications to ensure benefits for consumers, the environment and industry.

Efficient verification procedures

Effective market surveillance depends on efficient procedures, and endurance tests of even 1,500 hours ($62\frac{1}{2}$ days) last too long for market surveillance authorities to swiftly identify non-compliant products. We propose to maintain an 'early failure test' of 500 hours (and no more than 1,000 hours).

No laboratory is the same, and measuring light output is extremely difficult, even under uniform circumstances. Correcting these differences is done through the use of tolerances, which should be used by market surveillance authorities only and not by manufacturers.

Database for energy labelling

A new database is expected to operate as of 1st January 2019 — the EU Product Database for Energy Labelling (EPREL). Uploading product information for hundreds of thousands of models of light sources, including lamps and modules sold between 1 August 2017 and 1 January 2019, is not feasible given the current timeline and scope. Tight timelines may result in involuntary non-compliance [1].

A level playing field should be ensured between the various suppliers on the European market [2]. Market surveillance authorities should verify that all economic operators in the EU are indeed registered with their products in the database.

LightingEurope proposes, to limit the administrative load for industry by:

- postponing the database obligation for light sources to the entry into force of the new energy label
- reducing the scope to end-user replaceable light sources
- exempting products that have to be phased out by Ecodesign Regulation.

A vote on the final ecodesign and labelling rules is expected in Q4 this year and LightingEurope will continue to engage to shape a clear and positive regulatory environment for the industry in Europe.

[1] *We estimate that between 1 and 3 million luminaire models will have to be registered in EPREL initially. For lamps, we estimate that between 200,000 and 500,000 product models will have to be registered in EPREL in the first period before end of June 2019. From 2020 on, when the new delegated act on light sources will entry into force, we expect around 1.000.000 new light sources records to be uploaded in the database, making it so burdensome that would be hardly workable for light sources manufacturers.*

[2] *LightingEurope, Position Paper on the energy labelling database (Brussels, 23 February 2018).*

The Role of Governments in the Transformation of the SSL Industry

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Abstract

The introduction of solid-state lighting (SSL) has disrupted the global structure of the lighting industry. The potential for substantial energy savings and reductions in the environmental impact of lighting have led to considerable interest by national and regional governments in encouraging adoption. The most intense efforts have been in China, where federal, provincial and local governments have made substantial investments to drive the transformation and expansion of the lighting industry. These efforts are summarized and compared with government actions in other regions.

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Introduction

The pace of lighting technology development in the second half of the 20th century was glacial. The global industry relied almost entirely on four lamp suppliers and the small margins on lamp manufacturing provided little support for research. The situation changed dramatically at the beginning of this century as realization dawned that solid state lighting was about to emerge from the laboratory, opening up commercial opportunities in several large markets.

Over the next two decades, the established companies struggled to develop strategies to maintain profits while adopting the new light sources. Strong new competitors emerged, mainly in Korea and China, with substantial government support and little encumbrance from outdated production facilities. The opportunity to save energy encouraged national and regional governments to become involved, with encouragement from international organizations, such as the United Nations Environmental Program and the Climate Group.

One way that governments have become involved is through the development of regulations to restrict the choices available to customers. This is an extremely complex endeavour that leads to strong resistance by industry and some consumers, with pleas for exceptions and delays as well as philosophical objections in some regions. These issues are not discussed in depth here, but may be addressed in the accompanying presentation by Elena Scaroni of Lighting Europe. Instead we will focus on support for R&D and manufacturing, market development and quality control. Rather than commenting on each aspect for every region, we will just highlight those that have highest impact.

Research and Development

Korea

One of the earliest countries to develop a successful program of industrial support in SSL technology was South Korea. The Semiconductor National Lighting Program was set up in 1993–1996, with annual funding of about $20M, mostly from the national government and local authorities in Gwanju, the “City of Light” [1]. The R&D was coordinated through the Korea Photonics Technology Institute and the industrial participants included LG and Samsung.

During the past twenty years photonic research has been promoted at several other government-sponsored institutes, such as ETRI, KAIST, KIST and KITECH, along with a large number of excellent university groups. Although much of this activity is focused on display applications, the work has helped to sustain three of the leading global companies in SSL.

Japan

In April 1998, the Ministry of International Trade and Industry in Japan announced the “Light for the 21st Century”, a 5-year project bringing together 13 companies and 4 universities under the purview of the Japan Research Center for Metal-based Materials. The project targeted an energy efficiency “twice that of traditional fluorescent lamps”, through the use of thin, lightweight, GaN-based high-efficiency blue and ultraviolet LEDs [2]. Other goals were

- Ease of miniaturization
- Long life
- Simple structure with few components and easy controls
- High reliability through the use of all solid-state devices

This project focused on the leading technology, rather than on the simultaneous support of a variety of approaches. All elements in light production and delivery were included, from substrate selection through epitaxy (MOCVD) and phosphor application to optics and luminaire structures. The results were published in detail. The annual report for 2000 cited over 100 other publications along with 36 patent applications. The focus on a single approach followed the example of the successful US effort to rescue its semiconductor industry through the formation of Sematech in 1986.

China

National solid-state lighting programs were launched in both Taiwan and mainland China around 2003. The R&D program established with modest funding in 2002 by the National Research Council of Taiwan had an immediate impact on patent applications and the development of new processing techniques. Along with several strong

academic groups, the Industrial Technology Research Institute (ITRI) became one of the most productive research laboratories in both LED and OLED development. In 2004 a consortium of 11 companies formed the “Next Generation Lighting Project”.

In Beijing, as shown in Figure 1, the National SSL program was launched in 2003, with a very broad scope from basic R&D to manufacturing and market development. The growth of a strong research program was aided by the appointment of a Professor in Optical Physics at the Changchun Institute of Optics and Fine Mechanics, Dr. Cao Jianlin, as Vice Minister of the Ministry of Science and Technology (MOST). In the 11th 5-year plan, beginning in 2006, support for R&D in SSL was increased 10-fold to RMB 350M ($45M), growing again to RMB 600M in the 12th Plan in 2011. The research has always had a strong applied component. SSL patent applications have grown from 1400 in 2003 to over 30,000 in 2017.

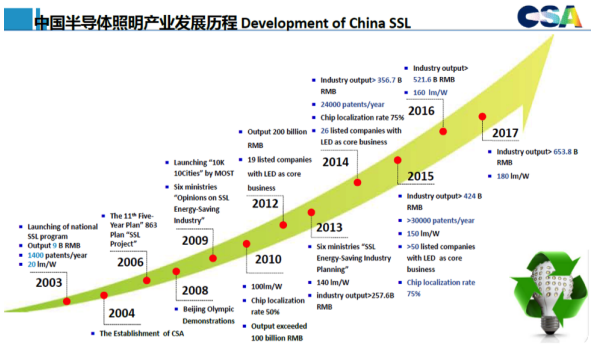

Figure 1: Development of SSL in China. (Source: Jinmin Li, CSA)

Financial support has come from local governments as well as from the national government in Beijing. Some regions have focused upon alternative approaches. For example, an industrial consortium was formed in the Jinsha River area to develop GaN on Si substrates, based on research at Nanchang University. Professor Fengyi Jiang, vice principal of Nanchang University was one of the founders of the leading company, Lattice Power.

The China Solid-State Lighting Alliance (CSA) was formed in 2004, with 46 members and headquarters in the Institute for Semiconductors of the Chinese Academy of Sciences in Beijing. With about 50 full-time staff and 100 part-time consultants, CSA now supports 200 working groups for almost 600 members. It organizes the China International Forum on Solid State Lighting (SSLChina), which has become one of the two largest technical meetings on SSL, along with the LED Professional Symposium in Europe.

Following the success of the SSL initiative, both national and regional governments are now expanding their support for wide-gap semiconductors, with the goal of capturing a greater share of the power electronics market and other areas of semiconductor applications, through the establishment of new research parks and the expansion of existing activities.

USA

The US Department of Energy began to support focused R&D in SSL around 2003. Following a report on the potential contribution to energy savings [3], Senator Bingaman had called for the establishment of a “Next Generation Lighting Initiative” with funding of $480M over a ten-year period. As can be seen from Figure 2, the annual appropriations only reached the requested level of $50M once, in 2011 when a special supplement was added as part of the American Recovery and Reinvestment Act (ARRA) [4]. The total funding has reached ~$400M over 16 years.

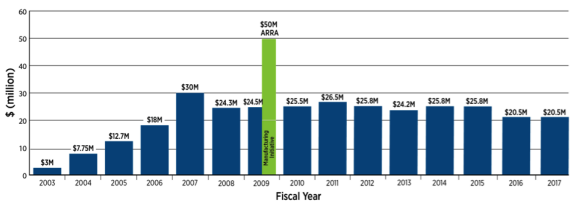

Figure 2: Government funding for SSL Program at US DOE. (Source: James Brodrick, US DOE))

This funding covers a wide range of activities and about 60% has been used to support R&D. The projects that were active at some time in 2017 included 30 LED projects ($28M) and 19 on OLEDs ($16M).

Europe

The European Commission began to support R&D in SSL through the Framework 6 Program, with at least 6 projects started between 2003 and 2005 with government funding of €23M. Funding grew significantly in the Framework 7 Program. Over 40 projects were started between 2008 and 2014, with a total EC contribution of more than €140M. Of this total €76M was devoted to projects based on LED technology and €64M on

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alternatives, such as OLED, perovskites and electroluminescent quantum dots.

In the first 4 years of the Horizon 2020 program, over 50 SSL projects have been initiated with EC funding of ~€125M. Only about 40% of this support has been for LED-based projects, with more now going to alternative technologies.

Additional funds for R&D have been made by national governments and regions, such as Saxony in Germany. Of special note was the investment of more than €100M in OLED development made by the German Federal Ministry of Education and Research (BMBF).

Manufacturing and Infrastructure

China

During the 11th Five-Year Plan, beginning in 2006, the Chinese SSL effort moved from research into prestigious demonstrations and building the necessary manufacturing capacity and infrastructure. Although initial plans for funding were modest, with a total of RMB350M (US$45M), support was expanded substantially in the second half of the period. Many incentives were offered by the national and regional governments, including direct subsidies for manufacturing facilities, low interest loans, tax breaks and land at very attractive rents. To facilitate the development of an effective infrastructure, the activity was concentrated in seven regions, Shanghai, Dalian, Nanchang, Xiamen, Shenzhen, Yangzhou and Shijiazhuang.

Although major demonstrations initially relied on imported LEDs, massive investments were made to fill the gap. SEMI reported that in 2011 Chinese companies spent over $1.2B on LED fabrication equipment. At the end of the 5-year period, the China Association for the Lighting Industry (CALI) reported that there were over 60 manufacturers of wafers and chips, 200 LED packagers and more than 5,000 manufacturers of LED lights.

Although this assistance was distributed broadly, substantial funds were directed at creating 20–30 companies that could compete on an international level. Sanan Optoelectronics, the dominant chip maker, has received over RMB 4B ($600M) in subsidies since 2008. According to LEDInside, subsidies accounted for 47% of Sanan's revenues in 2011 and 62% in 2012, but the contribution dropped to 20% in 2016 as sales rose. The total subsidies represent about 20% of the company's current equity of around RMB20B ($3B). Sanan now possesses over 20% of the global capacity for LED chips, with the total for all Chinese companies now being over 50%.

While the direct subsidies can be criticized as giving unfair advantage to favored companies, it is also apparent that they enabled MOCVD equipment suppliers Aixtron and Veeco to have their most profitable years and led to significant reductions in the price of LEDs across the globe.

Although government assistance played a major role in the growth of Sanan, the enthusiasm of Chinese investors has also helped. In mid-2018 the market value of the company was over RMB 80B ($12B), close to the combined valuation of Osram Licht and Philips Lighting. The number of publicly-listed companies has increased rapidly and the total profits of the 40 leaders grew by almost 50% in 2017. New industrial investment by these companies in 2017 exceeded RMB 70B ($10B).

The national government has drastically reduced its provision of LED manufacturing subsidies, but regional and city governments are still active. Digitimes has reported that local support totaled RMB 1.14B in 2015, RMB 1.26B in 2016, RMB 1.75B in 2017 and surged to RMB 2.30B ($350M) in the first-half of 2018. Again, the support has been highly selective, with Sanan receiving RMB780M and MLS, the leading packager, receiving RMB447M.

India

The Indian national government, led by Prime Minister Modi, realized the potential for SSL to make a significant contribution to solving the energy shortage and reduce the pollution from traditional energy sources. The UJALA program (Unnat Jyoti Affordable LEDs for All) was launched in 2014 as a market driven initiative, with strong policy support from the government [5]. It is claimed to be the world's largest zero-subsidy LED bulb program for domestic consumers.

Between 2001 and 2013 India had taken major steps to improve the energy efficiency of light by establishing a large capacity to manufacture compact fluorescent lamps (CFL), with an annual

production approaching 1 billion lamps from 60 manufacturers. However, between 2007 and 2012 annual sales of incandescent sales remained above 750M.

As described below, the key to the UJALA program was the supply of LED bulbs to domestic consumers at prices that were similar to those of CFLs and such that the whole cost could be recovered from savings on electricity bills over just a few months. The goal was to encourage manufacturers to switch to the production of SSL lamps through incentives in bulk purchasing projects, rather than by direct subsidies. Although LED chips would be imported, domestic packaging of LEDs would be introduced through collaboration of Indian and foreign companies, and Indian lamp factories would be converted to use LED sources. Ironically, the result has been that LED sales have primarily replaced those of CFLs and uncertainty about future availability led initially to an increase in the purchase of incandescent lamps.

USA

The federal government has been reluctant to grant direct subsidies to industry, partly to avoid having to pick “winners from losers”. One exception was in the “American Recovery and Reinvestment Act” of 2009, which led to a supplement to the DOE SSL program in FY2011, specifically for the support of manufacturing. Most of the selected projects involved research into new processing techniques, but two included the establishment of OLED pilot lines. The government contribution to each project was $4M, with an equal amount of cost sharing by the companies. Neither project met expectations, due mainly to reduced corporate commitment, as the economy expanded more slowly than expected.

Although regional governments in the US also often offer incentives to encourage the establishment of new manufacturing facilities, these do not appear to have had a major impact on the SSL industry.

Europe

Along with most national governments, the European Commission has a strong preference for supporting pre-competitive research and requires that most projects involve teams with participation by universities or independent research institutions as well as corporations. Support for manufacturing has come mainly through the development of new processing techniques. Direct support for the installation of manufacturing equipment has come mainly through the establishment of OLED pilot lines, for example in the PI-SCALE project. This leads to the production of prototype lights, but does not provide financial support for any high-volume manufacturing.

Southern Hemisphere

In almost all countries in the southern hemisphere, domestic lamp production had been dominated by GE, Osram and Philips. Almost all of their factories have been closed and it has been extremely difficult to build replacement facilities for solid state lamps. The gap is being filled by imports of both lamps and luminaires, mainly from China. For example, in Brazil imports of LED bulbs rose from 27M bulbs in 2014 to 230M in 2017, while LED luminaire imports rose from 16M in 2015 to 95M in 2017. Despite the deleterious impact on the trade balance and employment, few governments in countries with weak economies have provided effective support for domestic manufacturing, despite urging from the national trade associations.

The threat to domestic manufacturing is also of concern in countries with strong economies. For example, in an interview with the Lighting Council Australia, the General Manager of Frend Lighting Industries stated that although 70% of commercial luminaires are currently manufactured in Australia he feared that the ratio may fall to 10% in the future [6].

Market Development and Quality Control

China

Public demonstrations of SSL lighting played an important role in the growth of the domestic market. Some demonstrations were temporary, such as at the 2008 Olympics and the 60th National Anniversary Celebrations in Tiananmen Square in 2009. Others were permanent, including the lighting upgrade at the Great Hall of People in Beijing in 2012. CSA reported in 2013 that over 11M lamps had been installed in 3500 demonstration projects in 37 pilot cities. Over

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75% of these demos were outdoors for maximum impact. Ironically, many of the outdoor projects increased the demand for light and so may have led to conflict with the goal of energy reduction.

Government influence over new building procedures has also been important. New residential, commercial and public buildings provided a market for over 750M lamps. The CSA has also stressed the opportunities to adapt SSL lighting for specific applications. For example, the demand for special lighting in medical facilities is estimated as 6M units, worth RMB 58B ($850M). The city of Beijing has recently invested RMB 110M for improved lighting in schools to combat the deteriorating eyesight of students. Because of the shortage of agricultural land and increased congestion in cities, both national and regional governments have promoted agricultural applications of SSL and the role of lighting in smart city developments.

The results of government promotion have been impressive. Unit penetration of LEDs in the domestic general lighting market rose from 42% in 2016 to 65% in 2017, with sales of 4.7B LED lights. Savings in electricity use in 2017 were estimated as 188 TWh (~20% of anticipated demand) and the reduction in CO_2 emissions as 178M tons. Almost 6B lighting products were available for export and the value of exports grew to $13B, with half going to Europe and the US.

Since the rapid growth of the SSL industry attracted over 5,000 manufacturers, the government and trade associations have always been concerned about quality control. In 2017 CSA was involved in the publication or development of over 60 standards relating to SSL. As an example of continuing work, CSA has released a report T/CSA/TR 007/2008 on the development of standards relating to the impact of lighting on health.

A wide network of testing laboratories has been set up to support these standards, both through certification processes and random testing. For example, in tests carried out in Anhui province in March 2018, 25% of the products failed due to inadequate performance or safety concerns.

Japan

For many years Japanese companies and consumers have shown strong concern about energy efficiency and environmental pollution. Fluorescent tubes have always been more popular than incandescent bulbs, even in residential applications. Energy efficiency standards for fluorescent lamps were first introduced in 1993 and energy labelling became mandatory in 1998. In 2005 the average efficacy of residential lighting was 50 lm/W, while the average for all applications was 65 lm/W.

Despite this record, the Japanese government and industry were among the earliest proponents of solid-state lighting. Tax incentives were offered in 2005, and in 2009 LED lamps were added to the list of products qualifying for the $11B Eco-Points program, which gave vouchers or gift certificates to purchasers of energy efficient appliances. For a period in 2010, sales of LED lamps reached 19% of total sales by volume and 60% by value, according to GfK Marketing Services. The Eco-Point program was extended following the Fukushima disaster in 2011. The government also introduced a real-time exchange program and sales of LED lamps rose more than three-fold between March and July 2011.

Incandescent bulbs have not completed disappeared. In 2017 the Tokyo Metropolitan Government estimated that they were still in use in 40% of residences. A campaign was launched to exchange one LED bulb for every two incandescent bulbs brought to any of 800 retail stores in Tokyo.

For many years now LED products have dominated sales of luminaires. The situation for lamps (bulbs and tubes) seems to be very different. According to the Japan Lighting Manufacturers Association, annual sales of LED lamps grew from 22M in 2012 to 28M in 2014 but then fell to 24M. Unit sales of fluorescent lamps are still much larger, having fallen only slowly from 238M in 2012 to 158M in 2016.

In November 2015 the Japanese announced that as part of its support for the Minamata Convention on mercury, the production and import of fluorescent lamps would be banned, beginning in 2020. This proposal was not received well by industry and it seems unlikely that a complete ban could be imposed abruptly.

India

As noted above, the Indian Government launched an ambitious program in 2014 to promote the adoption of LEDs without providing subsidies. The program had two major components

- Domestic Efficient Lighting Program (DELP) — The goal was to supply 770M general service bulbs, leading to annual savings of 100 TW h in electricity and 400B rupees ($6B) in consumer bills.
- Street Light National Program (SLNP) — The replacement of 35M street lights, resulting in savings of 9 TW h in electricity and cost savings to municipalities of 55B rupees ($800M).

The general service LED bulbs were obtained through bulk tenders, beginning in January 2014 with 0.75M bulbs purchased at an average price of 310 rupees (∼$4.50). The price fell rapidly, with 100M bulbs purchased in two tenders around the end of 2016 at around 40 rupees ($0.60). Distribution costs have been minimized through the oversight of the Energy Efficiency Services Limited and the cost to consumers has fallen to 50 rupees in some areas. Most customers have been offered the option of paying most of the cost through monthly surcharges on their electricity bill. Over 300M LED bulbs had been distributed through this scheme, as of June 2018. The annual savings are estimated as 39 TW h in electricity, 32 Mtons of CO_2 emissions and 160B rupees in consumer bills [5].

Quality control has been exercised at all levels, supported through standards and testing laboratories [5]. Failure rates reported in 23 states vary from 0.3% to 0.97%, with a national average of 0.48%.

The trade association ELCOMA [7] estimates that total sales of LED lamps between 2014 and 2017 included 654M bulbs and 142M tubes. Market penetration for LED in 2017 was 28% in units and 68% in value. Ironically most of the LED sales have been as replacements for CFL lamps, for which sales fell from 453M in 2013 to 131M in 2017. Sales of incandescent lamps grew from 780M in 2013 to 904M in 2014 and then fell only gradually to 771M in 2017.

Implementing the street light program has proved to be more difficult, due to production, financing and political problems. Vendors were required to offer a seven-year maintenance plan and the financing was arranged so that there would be no upfront charge to local municipalities. Installation began slowly and is now at around 250K per month. Total installations had reached 6.3M lights by mid-July 2018, suggesting that the goal of replacing 35M lights by 2019 will not be met.

Significant differences between regions in the climate and the reliability of the electricity supply make quality assurance more difficult, but an independent analysis of 131,000 streetlights in 5 areas by Price Waterhouse Coopers found that the failure rate varied between 0.86% and 2.22%, with an average of 1.06%

USA

In addition to the R&D program described above, the DOE SSL program has offered broad support for the adoption of LED and OLED lighting. Highlights include:

- Instituted the DOE SSL Lighting Facts Program that published performance data on over 70,000 LED products from almost 3000 manufacturers.
- Sponsored over 500 tests of LED products by independent laboratories through the Caliper Program, which also analyzed trends in the Lighting Facts database.
- Through the Gateway Program, oversaw about 30 comprehensive field studies of LED installations, both indoors and outdoors.
- Sponsored annual reports on LED adoption rates and energy savings
- Organized annual workshops and round tables and published regular webcasts and web postings to encourage interactions between stakeholders in all parts of the SSL industry.
- Supported the formation of the Municipal Solid-State Street Lighting Consortium
- Sponsored the L-Prize and the annual Next-Generation Lighting Competitions
- Set up a test-bed for connected lighting infrastructure, to study aspects such as interoperability and cyber security

Although lighting professionals have fully endorsed SSL technology, adoption by consumers has been slower. Data from the National Electrical Manufacturers Association [8] for the 4th quarter of 2017 show that highly inefficient bulbs still accounted for more than half

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of sales of general service lamps. Perhaps the brightest aspect of this data was that 23% of the sales of linear tubes contained LED sources.

More detailed data on SSL adoption can be found in the DOE reports [9]. By the end of 2016, penetration of the installed base was 12% for indoor lights and 30% for outdoor applications. Greatest penetration was found for small directional lamps at 48%, while linear fixtures lagged at 6%.

Southern Hemisphere

Because of space limits, we will focus on just two aspects, street lighting and lights for communities without access to the electrical grid. In both cases, raising the financing needed for large-scale conversion can be more difficult than solving the technical challenges.

The lighting industry in Australia and New Zealand has worked closely with government agencies to promote the adoption of SSL in street lighting. A comprehensive roadmap was published by the Institute of Public Works Engineering Australasia in December, 2016 [10]. The development of a coordinated approach was difficult because 90% of the streetlights in Australia were owned by electricity network companies, which are often not keen to reduce their revenues through increased energy efficiency. As of mid-July 2018, the Australian Energy Efficient Lighting Counter was approaching 500K lights, or 22% of the installed base [11]. These have been installed by about 110 local councils (out of 570 total), most of these being in South Australia.

In New Zealand over 90% of the 370K streetlights are operated by local authorities. To reduce the burden on those local municipalities, the New Zealand Transport Agency announced the availability of 85% cost sharing for SSL upgrades. In August 2015, Auckland Transport announced a plan to award contracts to replace 44K of their 110K street lights and forecast that the remainder would be converted in 4–5 years. However, in April 2018 it was estimated that only 17,000 lights had been replaced.

Because of rapid rises in the cost of electricity, Brazil has been eager to convert its 18 million street lights to SSL technology 2016. Although ownership of the lights has now been transferred to public authorities, Brazil has over 5000 municipalities. Three of the largest cities, Belo Horizonte, Rio de Janeiro and Sao Paulo had developed plans to replace their 1M lights, but high domestic interest rates made it very difficult to finance the ventures without international assistance. In 2016 the Climate Group and World Bank conducted a comprehensive study of the opportunity to arrange financing for all parts of the country, by encouraging smaller municipalities to join together in large groups [12]. Little progress seems to have been yet in implementing these plans, but several specific financial plans have been coming together in 2018.

One of the greatest challenges facing governments in many countries in the southern hemisphere and equatorial regions is to provide lighting and other essential services in areas with no access to the electric grid. During the past decade it has become clear that the use of small or medium-sized renewable energy sources is more effective than connection to traditional high-voltage grids. Lighting often provides the first step towards energy self-sufficiency for families, both because of the importance of artificial light in supporting personal and social development and also the economic savings that can be applied to acquiring larger systems. The development of SSL has contributed greatly to the affordability of off-grid lighting systems. The cost of delivering a constant level of lighting service declined by 67% from 2012 to 2018, due mainly to gains in LED efficacy [13].

International governmental cooperation has made a major contribution to this development through the activities of Lighting Africa and Lighting Asia [14], set up by the World Bank and the International Finance Corporation, in conjunction with industry through the Global Off-Grid Lighting Association (GOGLA). National governments can help greatly in at least three ways.

- Facilitating financing for consumers through loans or pay-as-you-go schemes
- Off-setting subsidies for traditional fuels, such as kerosene
- Supporting quality control procedures, following guidance from GOGLA

Conclusions

Governments have followed a variety of approaches to respond to the rapid advances in lighting technology, the opportunities for

significant energy savings and the threat to traditional manufacturing. The results are often not clear and so perhaps the best way to conclude this paper is to ask whether our experience over the past two decades provides insight into the following questions.

- Are regulations or direct subsidies effective ways to promote environmental protection?
- Are regulations or subsidies effective ways for governments to encourage consumers to adopt new technologies that cost more initially but have lowest overall cost-of-ownership?
- Is it better for governments to limit support for R&D to precompetitive work or also to help assist leading domestic companies to compete on a global scale?
- Is it appropriate for substantial portions of government support of R&D to be focused on alternative approaches not favoured by the leading industrial laboratories?
- What are the best ways for governments to support domestic manufacturing in a period of rapid technology change and intense international competition?

References

[1] Susan Walsh Sanderson et al, "Lighting Industry: Structure and Technology in the Transition to Solid State", Alfred P Sloan Foundation Conference on Industry Studies (2008). http://web.mit.edu/is08/pdf/Lighting\%20to\%20distribute\%2010Apr2008.pdf

[2] "Light for the 21st Century" — Translated by OIDA and Sandia National Laboratories: http://www.sandia.gov/~jytsao/L21C.pdf

[3] Roland Haitz et al, "The Case for a National Research Program on Semiconductor Lighting", Sandia Report 2000–1612; http://www.sandia.gov/~jytsao/hpsnl_sand_report_2000.pdf

[4] https://www.energy.gov/sites/prod/files/2017/02/f34/brodrick_rd-update_longbeach2017_2.pdf

[5] http://www.ujala.gov.in/

[6] https://www.lightingcouncil.com.au/wp-content/uploads/2018/05/1804-April-Illuminations.pdf

[7] http://www.elcomaindia.com/wp-content/uploads/Lighting-Industry-India-2017.pdf

[8] https://www.nema.org/Intelligence/Pages/Lamp-Indices.aspx

[9] https://www.energy.gov/sites/prod/files/2017/08/f35/led-adoption-jul2017_0.pdf

[10] http://www.slsc.org.au/slsc/slsc-publications/slsc-roadmap

[11] http://www.ironbarksustainability.com.au/lighting/

[12] https://openknowledge.worldbank.org/handle/10986/29537

[13] Arne Jacobson, "Technical Advances in the Off-Grid Solar-Sector", Global Off-Grid Solar Forum https://www.gogla.org/sites/default/files/documenten/s1_-_technical_advances_in_the_ogsector_-_serc.pdf

[14] https://www.lightingglobal.org/

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Future-Proofing Lighting Control Systems

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Abstract

This article proposes a solution which builds future-proofing into the architecture of a smart lighting system. Its core principle is that the design of a smart, networked lighting system today should allow for the simplest possible method for connecting the main lighting devices (sensors, switches and luminaires) to each other locally. The architecture should also make provision for the addition of low-cost, easily replaceable gateways which operate as a “protocol translators” for communications between end nodes and a building control system or cloud interface.

By using this architecture, a change from an obsolete building-control technology to a new technology involves nothing more than the replacement of a small number of gateways, while most of the installation (the end nodes) remains unchanged. Future-proofing is an inherent characteristic of the architecture.

This article describes this approach to the implementation of smart lighting systems for use in the IoT. It examines:

- The point-to-point or point-to-multi-point network topologies required to allow for local connection of nodes without recourse to a gateway.
- The features of three wireless networking technologies (Zigbee, Bluetooth, EnOcean), and identifies whether they are suitable for implementation in this kind of smart lighting network architecture.
- The operation of low-cost gateways in the role of “protocol translator”, and the availability of commercial off-the-shelf products that can implement this role today

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Lighting control uncertainties

The operators and buyers of new building automation and lighting control systems are in a bind: there are clear and strong benefits to be gained from the implementation of connected, intelligent and cloud-enabled lighting technology, including improved ability to control and monitor lights, more flexibility and reduced operational expenses.

But while the technical capability to implement new smart lighting systems exists today, it is unclear which platforms for building automation and cloud connectivity are going to thrive, and which will suffer the "Betamax" fate of falling out of use and becoming obsolete.

This means that the owners and operators of building automation systems are exposed to the risk of buying, installing and commissioning sophisticated smart lighting technology that runs into a commercial dead end and has to be expensively replaced after only a few years of service with a more up-to-date technology.

The question is, how can buyers and building managers future-proof their investment so that they gain the greatest possible immunity from the risk of obsolescence?

It is in fact possible to implement a solution which builds future-proofing into the architecture of a smart lighting system. Its core principle is that the design of a smart, networked lighting system today should provide a simple method for connecting the main lighting devices (sensors, switches and luminaires) to each other locally in a standalone fashion without requiring gateways. The main lighting devices should communicate via an interoperable communication standard which is supported by multiple device vendors. Interoperability provides multiple options to mix and match devices and luminaires in a single installation project.

The architecture should also make provision for optionally adding low-cost, easily replaceable gateways which operate as simple "protocol translators" for communications between the end nodes and a building automation system or cloud interface.

But this solution needs the building manager to make the right choice now of connectivity technology for the local devices, to ensure their permanent compatibility with gateway products which can translate control signals for any current or future building-automation protocol.

The architecture of building-automation systems

There is a clear appeal to the idea of integrating the various elements of a building automation system (such as fire safety systems, intruder alarm systems, access control systems, Heating, Ventilation and Air-Conditioning (HVAC) as well as lighting controls) via a single communications and control technology.

Various attempts to provide a wireless technology framework have been made: perhaps the best known is Zigbee, which provides a short-range, low-power wireless networking protocol and a language which allows many kinds of smart objects to work together. The challenge is that many device vendors have implemented their own custom version of Zigbee, which has impaired the interoperability of the protocol. Furthermore, the Zigbee gateway plays an additional role of managing the routing of the network, which adds an extra level of complexity for commissioning and when interfacing to a building automation system or the cloud.

A problem arises from the nature of technology development for building automation applications: there is in fact no single protocol or technology that is unanimously adopted for building automation. Each industry which touches on the domain of building automation, such as lighting, fire and security, access control, HVAC and so on, has deep, independent roots, and in many cases has developed automation or control technologies suited to its own particular needs. Until recently, lighting was not a significant part of building automation systems because there was no simple lighting control solution that could interface to existing HVAC or other building control systems.

The lighting industry has largely standardised on DALI in Europe, 0–10 V control in North America, and on PWM control in Japan; each technology provides a common signal for controlling discrete lighting devices such as LED drivers and ballasts (see Figure 1). The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) developed the BACnet protocol to

meet building automation and control needs. In Europe and China, KNX is a second popular building automation protocol. And the challenge in integrating lighting control into building automation is that there are no LED drivers or ballasts that natively support BACnet or KNX.

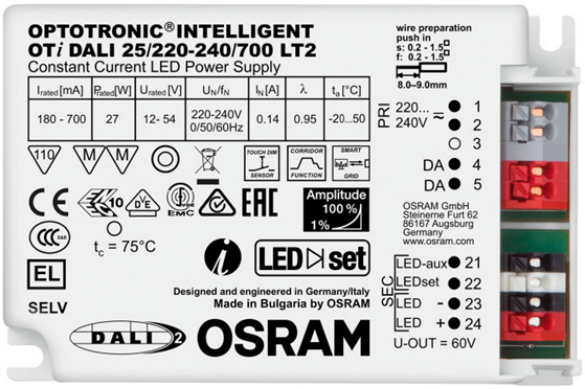

Figure 1: The Osram Optotronic LED driver, which supports the DALI interface. (Photo credit: Osram).

Here lies the problem for manufacturers of luminaires and other lighting equipment which wish to make their products ready for operation as part of the IoT: in the future, any one of these communications technologies might be extended to become a universal protocol for building automation. Or a new universal building automation technology might emerge. No-one currently knows.

And what happens if a manufacturer of lighting equipment makes a bet now on any of the existing protocols, whether BACnet or KNX or Zigbee or other? Whichever it is, this choice will weigh heavily against it in the minds of buyers, because they will worry that if at some point in the future the protocol falls out of common usage and is superseded by another, their investment in now-obsolete lighting equipment will be wasted and they will need to replace it with updated luminaires, switches and controls.

The requirement: a future-proof short-range wireless connection

While lighting equipment manufacturers cannot predict the future, they can build resilience into their products, so that they are able to adapt to whichever changes the future brings while giving customers the functionality that they desire today.

The typical requirements for IoT-ready smart lighting systems are:

- The ability to respond intelligently to the immediate environment in which the lighting equipment operates. This is achieved by connecting lighting fixtures to switches and to sensors, such as ambient light sensors for daylight harvesting, and infrared proximity sensors for presence detection.
- The ability to connect to a building-automation network for integration with building-wide controls, and if appropriate to provide connectivity with the cloud.

For ease and cost of installation, wireless connections between local devices (switches, sensors and fixtures) will be strongly preferred. These local connections only need to support simple operations, such as switching lights on or off when people are present, or dimming the lights when daylight is being harvested. These local connections do not need a sophisticated building automation protocol.

Instead, either one of two standard short-range wireless technologies provide built-in support for these simple lighting controls: one is Bluetooth Mesh networking, the other is EnOcean. Both are ideally suited to lighting applications, because they devices from different vendors are interoperable, and do not require gateways to implement a system. Lighting-specific profiles ensure interoperability between luminaires from different manufacturers. Furthermore, these technologies support batteryless operation through the use of harvested energy where switches, for example, are powered by the kinetic energy generated by the user who presses the switch.

An advantage of Bluetooth Mesh is that it provides scope for direct control of devices via the user's smartphone or tablet. It also supports over-the-air updates and beaconing. An advantage of EnOcean technology is that it operates at frequencies below 1 GHz, which makes the technology more robust against interference, and extends the radio's range.

Most importantly, anyone who is intending to invest in smart lighting equipment can be sure that both Bluetooth and EnOcean have a long future ahead of them for commercial buildings. The global installed base of Bluetooth devices

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guarantees its future support, and EnOcean technology has already been installed in more than 400,000 buildings. The EnOcean Alliance has more than 400 members supplying more than 1,500 interoperable products.

Lighting devices, then, can operate locally via either a Bluetooth Mesh or EnOcean network. But they also need to be compatible with any future building automation protocol. This future-proofing is achieved by excluding support for building automation protocols from the lighting devices, and locating it instead in gateways operating as "protocol translators" between lighting devices and the building automation network (see Figure 2).

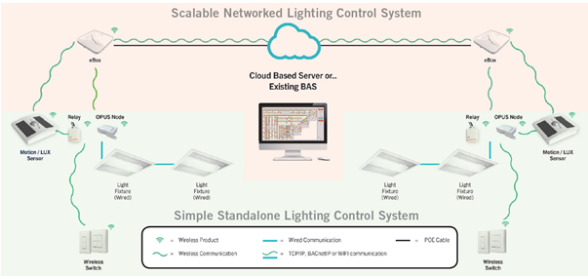

Figure 2: An EnOcean-based stand-alone lighting control system can be scale up with optional eBox protocol translator gateways to interface with building automation systems or the cloud.

The advantage of this approach is that in a medium-sized or large installation, the gateways will be few in number, and conveniently located for maintenance and replacement. This is in contrast to the lighting devices, which will be numerous, and located for the convenience of the user rather than the installer. Replacing the gateways, therefore, is far easier and more cost-effective than replacing an entire lighting installation.

With this device-and-gateway topology, a building owner might install a new building automation system based on the BACnet protocol today. If BACnet is superseded in future by some as yet unknown and superior technology, the building owner can retain all the existing lighting control devices and luminaires and connect them to a new building automation network simply by removing and replacing a small number of gateways, and configuring the new gateways to operate with the existing lighting equipment.

The Zigbee gateway complexity

One of the features of Zigbee networks is that devices must be connected via a gateway since the end devices (switches, sensors, luminaires) cannot directly communicate with each other. The operation of a Zigbee network depends on the existence of a gateway to route signals to and from devices and to manage the network (see Figure 3).

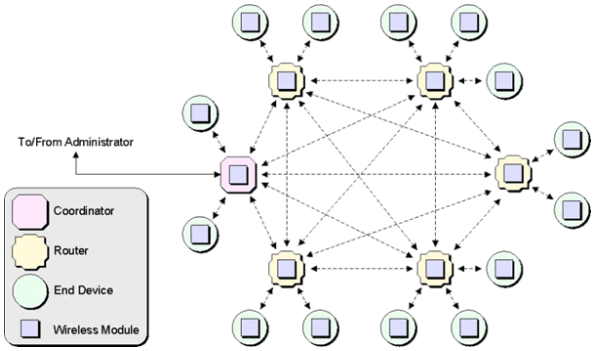

Figure 3: Architecture of a Zigbee network in which mandatory gateways route traffic between end nodes (Credit: Synapse Wireless).

A Zigbee gateway does not appear to solve the lighting industry's future-proofing challenge. First, the Zigbee gateway cannot be a simple protocol translator, since it also manages the network. And since interoperability between vendors which adopted Zigbee is limited, changing the gateway is not straightforward. Second, due to the additional complexities of implementing a Zigbee network compared to some more recent wireless technologies, the rate of new vendors implementing Zigbee in their devices has decelerated by comparison with technologies such as Bluetooth.

To future-proof the lighting control installation, the gateway should only be an optional device, and it must only act as a protocol translator to the building automation system or the cloud. Models of such gateways are already available. The eBox 2.0 from Magnum Energy Solutions (see Figure 4) is a BACnet IP gateway which interfaces multiple wireless EnOcean devices to a BACnet network, as previously shown in Figure 2.

If the building manager decides to change from a BACnet-based system to an Amazon AWS-based system at a later point, all that is required is to change the gateway from the eBox to the Magnum Energy Solutions cBox gateway: the luminaires, switches and sensors would remain

Figure 4: The eBox 2.0 EnOcean-to-BACnet gateway from Magnum Energy Solutions.

the same. Furthermore, Magnum gateways support EnOcean devices from other EnOcean product vendors, because the EnOcean protocol supports interoperability. Gateways supporting protocol translation from Bluetooth Mesh are already in development that will enable similar flexibility to the EnOcean types of gateways.

Conclusions

The design and implementation of secure and future-proof smart lighting equipment compatible with building automation systems depends on the integration of multiple device types, typically from more than one manufacturer. Ensuring the compatibility of each component is the primary benefit of selecting an interoperable standard such as Bluetooth Mesh and EnOcean.

What building and facilities managers are looking for is piece of mind while saving operational costs. It will also be important to educate specifiers, architects, engineers, system integrators, ESCOs and contractors on the benefits of interoperable future-proof solutions for managing the operation of a building.

Technology keeps advancing at rapid pace but we must clearly understand the channel and all its various stakeholders regarding how new technology is adopted to ensure that new solutions and services are widely accepted, where this is especially true for commercial lighting control.

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Managing Connected Lighting Solutions in Real Life

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Abstract

Commercial buildings are rapidly becoming more efficient, comfortable, flexible and generally more adaptive to their use and to the occupants' needs. The evolution of Internet of Things (IoT) technologies is booming with the purpose of delivering smarter, more automated and better-connected systems in new and existing buildings. Large-scale deployment continues to present a challenge for the industry because systems and practices remain highly "siloed" from the design to operation perspectives. Poor and costly integration between different systems, unclear ownership of IoT infrastructure and process gaps represent three substantial obstacles currently in the way of large-scale adoption but new technologies and approaches are successfully overcoming these obstacles.

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Ethernet Based Connected Lighting

The ability to migrate lighting controls to IP-based infrastructure makes the lighting a key IoT building asset that can be controlled synergistically along with other building functions. More integration means not only better control leading to drastic energy savings, increased occupant comfort and productivity performance, but also more meaningful data being collected by a distributed sensor system as part of the lighting network infrastructure. The use of IP lighting in commercial buildings is growing rapidly, and several such large-scale projects are getting underway in 2018. A real-life large scale installation will be used here to illustrate the unique role that IP lighting covers in merging together the Information and Operational worlds not only from a technology perspective but also in the areas of design, operating and maintenance processes and ownership. A novel digital building Integration approach is shown here as an effective way towards mass adoption and scale deployments of the Network Connected Solution serving as backbone Infrastructure for the digital buildings of today and tomorrow.

Drivers for IoT adoption and the role of connected lighting in a real project

The imposing 52 story granite skyscraper in Downtown Atlanta Georgia, headquarters of industry giant Georgia Pacific (GP) is an iconic building that is becoming one of the largest Power over Ethernet (PoE) based network connected lighting installations in North America and in the entire world. This project is known as “Blue Sky.” Let us take a journey within this real-life project deployed on a large scale to learn deeply about the drivers, the challenges, the opportunities and the value of investing in a building IoT infrastructure. The decision to adopt Network Connected Lighting as an IoT platform for the “Blue Sky” project was rooted in a key differentiator: demonstrated use cases, as opposed to projects of the past that were often driven solely by technology. These are some of the main goals the customer wanted to achieve:

1. Attract and retain talent and workers in a dynamic and fast-evolving workforce demographic scenario
2. Solidify its brand strength beyond the traditional market and geography
3. Use of technology connecting to resources beyond internal building systems to make more intelligent and adaptive choices about the present and future
4. Increase profits, achieving a more productive environment and optimized space utilization
5. Use data harvested from a highly granular sensor array and other data streams to impact the core business within the building, not just the building itself. In this perspective the role of connected lighting as an IoT ecosystem resides in the ability to stream building data to “company data lakes” and within these repositories use “in-building information” from connected devices mixed with external data streams to develop specific actionable insight targeted at different stakeholders far outside of just building management.

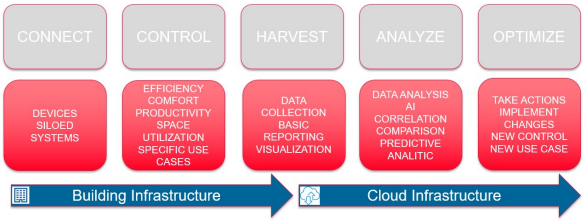

Figure 1: Digital Transformation process for Smart Buildings.

Synergistic Building from Theory to Practice

The highly integrated building resulted in the Blue Sky project is clearly not composed of one system controlling all but on the contrary, different specialized and highly optimized systems and functions integrated synergistically. A key fact is that the building industry has grown up in silos. In response, the network based connectivity nature of the lighting solution of choice has shown not only the expected characteristic of seamlessly connecting devices within the system but also the ability to interconnect silos for a more organic building automation. Network connected lighting implemented from the early stages of the project gained a major role offering itself as the main sensory network in support of other systems.

Let us now focus on some use cases that show

the IoT nature of a connected lighting system, specifically looking at the system as a sensory network in support of other systems.

Intelligent presence-based Scheduling and Audio Video

Figure 2: Connected Rooms with smart scheduling integration.

Space utilization and its optimization have been critical aspects in the project (considering that each floor features more than 70 spaces between conference rooms, break out rooms and private offices) bookable via a scheduling system. Each room also integrates an AV system to serve the users. The ability to implement presence-based scheduling and automated AV power-up was the main reason for presence detection in each space. Having the connected lighting system already equipped with occupancy sensors clearly manifested the network sensory nature of the connected lighting system. Not only are the same occupancy sensors implemented for smart occupancy-based lighting automation, they have also been utilized to support AV activation and real time occupancy data for room scheduling and booking. The cost savings in the hardware deployed in the building (around 100 zones per floor on average require an equivalent number of occupancy sensors multiplied for total number of floors for each system) was significant at this scale. The project used only 1/3 of the occupancy sensors compared to deploying a sensor for each individual system, avoiding the waste of using 3 similar devices. The cost savings go well beyond those of the unnecessary sensors: additional savings in installation, commissioning and maintenance are also realized. Coming to the space utilization use case, now it is possible to book each room from scheduling system installed on the user computer and, if after 15 minutes there is a “no show” detected by the connected lighting occupancy sensor, the room is “released” and can be re-booked by other users. Also there is the possibility to book the room “by presence” detected by the sensor if the room is available, simply by walking into the space. This intelligent and dynamic scheduling is projected to deliver great returns to the company. Data analytics will take care of running metrics and performance analysis on space optimization in terms of time savings and capacity to host the needs of each department on each floor.

Figure 3: Molex POE Gate Way and Temperature/Humidity sensor.

Use Case Connected Lighting granular deployed Temperature, Humidity sensor

Usually BMS and HVAC system have few thermostats in the building. The ability to deploy a granular array of temperature and humidity sensors leveraging the connectivity already in place, thanks to the connected lighting POE nodes, allows the accurate temperature and humidity sensing capability for each space at a fraction of the cost of a stand-alone traditional HVAC solution. Having the network connected lighting system seamlessly integrate with the BMS opens the door to additional use cases and integration in addition to improved HVAC control for each individual space. The connected lighting network is able to provide air quality, CO_2 and pressure sensors.

The open and scalable platform also allows the integration of future sensors such as personnel counting, people and asset tracking, audio sensors and others without additional cost to the infrastructure.

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Figure 4: Molex IOT Project design with sensor layer.

Some other "lighting specific" use cases

Bio-dynamic Lighting Control: the lighting control implements a simulated natural circadian cycle during working hours. The design aimed to minimize glare on the monitors, offering a natural-looking lighting environment to enhance comfort and productivity.

Predictive maintenance and improved reliability: in addition to the temperature and humidity environmental sensors stand alone, some lights also feature in-fixture sensor module with temperature sensors embedded. The combination of temperature readings and correlated color temperature (CCT) readings can help predict the lifetime of the light and also assist in predictive and preventive maintenance. The integration of the Molex Network connected lighting with a building management system (BMS) allows the ability to implement a demand response mechanism during peak times and also to control lights at a zone level in support of other events such as alarms.

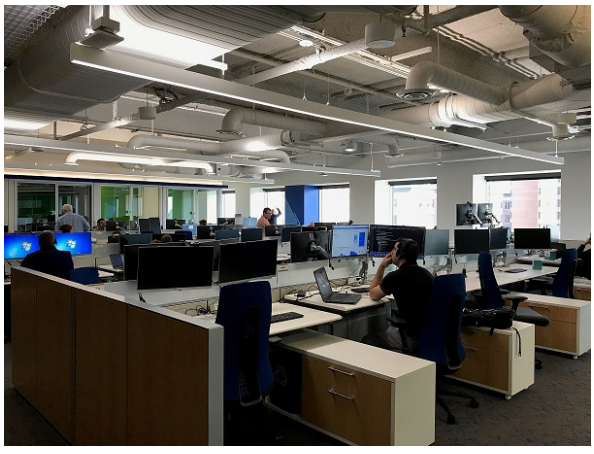

Figure 5: Desk Zone areas use linear fixtures with direct and indirect lighting distribution. Each fixture is white tunable (CCT range 2700–5700 K).

Network Connected Lighting Energy Monitoring

Punctual Energy consumption monitoring: The system has great freedom and ability to monitor lighting system energy usage. Energy usage can be monitored at the fixture level and at the network switch port level. The system can also monitor energy usage at zone and floor level as well as at network switch and rack levels. This data base of power monitoring information will be very important for predictive maintenance and efficiency analysis.

Figure 6 shows the power monitoring for a set of UPOE Network switches serving different zones. UPOE switches serving different zones have different power consumption curves. Power monitoring at each individual UPOE port is also shown. From the graphs emerges a correlation between lighting energy consumption and space user density. During lunchtime the dip in the energy curve represents a much lower occupancy presence in the building. Occupancy sensors are programmed in terms of time out (time after which the lights start to dim down) and fade time (the time necessary for the lights to dim down to zero after the no-presence detection count starts.) This implementation allows energy savings in a vacant space without the harsh on/off transition inherent in local or rudimentary lighting control.

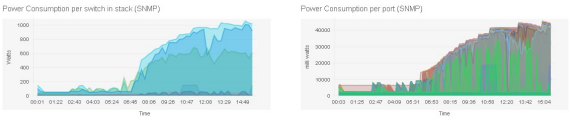

Figure 6: Power monitoring at network switch and UPOE port level.

Why a System Integration approach for Connected Lighting?

The above use cases and successful integration describe the key role and the ability of network connected lighting to be the ideal system driving IoT applications in smart buildings. Thanks to the fact that connected lighting is a needed function and thanks to its ubiquity in the building space, it becomes the natural center to interconnect four different worlds: Information Technology, Operation Technology, Traditional Building Automation Control and Cloud Services.

What are the main challenges that network connected lighting encounters in being promoted for the role described above? The reality is that these worlds speak different languages, are driven by different objectives, implement different practices and their ownership resides in different perimeters. The challenging goal of interconnecting these four worlds has been solved by Molex using a System Integration approach to the connected building solution in which lighting serves as the main vehicle. The system integration approach seems to have solved several obstacles and offers a line of minimal resistance and maximum penetration for the success of the project.

Why a System Integration approach for Connected Lighting?

There is a need to create processes and practices touching all aspects of a project from the pre-design phase to post-installation and maintenance.

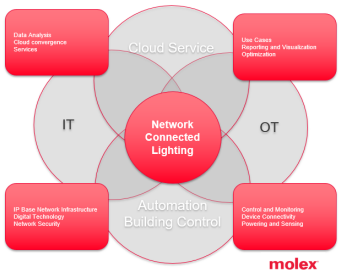

Figure 7: The central role of network connected lighting in building IoT projects.

- Important aspects in the Pre-Design phase: The network infrastructure usually already exists within the architecture of the corporate network and it is under the administration and management of the corporate IT department. IT's primary responsibility is to keep the data network secure, up and running, and to avoid anything that can possibly put at risk the network itself. From IT perspective one of the main challenges is to have a building system such as network connected lighting and main business system on the same network. It is very important to work with Corporate IT and discuss all the implications. Corporate IT should be considered the ultimate authority to approve a network design/architecture that supports connected lighting. The pre-design phase is characterized by providing good documentation that explains the IT properties for all aspects of the connected lighting system: security, ports, physical requirements, addressing, and a good network diagram. This is one of the main gaps in the lighting industry since lighting companies usually are not equipped to provide design specifications and/or guidelines in relation to the IT scope. The system integrator (SI) approach will clearly help in this direction and as project leader for connected lighting the integrator is also able to maintain good communication with IT during the design, installation and commissioning phases.

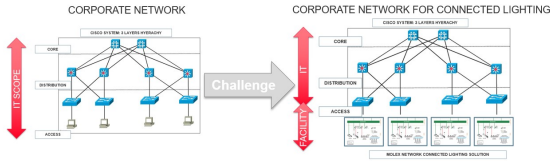

Figure 8: 3 levels Corporate network hierarchy and connected lighting challenge.

- Important Aspects of the Design phase: The design process for a network connected lighting and IoT solution requires the ability to create a design package that merges the architect/lighting design and MEP (mechanical, electrical, plumbing) aspects into those of IT, digital power and connectivity. The system integrator processes developed have been optimized to consolidate a Connected Lighting and IOT design package. It is very important to have design rules and documentation in place which will maintain a consistent approach independently from project geography and/or local contractors. From lighting design prospective, several POE light products from different lighting manufacturers were successfully used in the Blue Sky Project. This is an extremely important example for the industry to follow: avoiding the limitations of using a single lighting manufacturer source. The ability to integrate connected technology with already-existing product offerings from various collaborators such as H.E. Williams, Spectrum Lighting, Deco Lighting, Waldmann, JLC Tech, and many more is a key element to accelerating Network Connected Lighting into new and existing spaces as demonstrated in this project.
- Installation and Commissioning: A certified integrator is responsible for overseeing the

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installation for network and lighting aspects. Also the certified system integrator is the responsible authority for commissioning the entire connected lighting system. In particular, concerning aspects related to IoT application and use cases, the SI is responsible for guaranteeing the service of the connected lighting infrastructure as sensory network for Cloud data service and synergistic integration with other systems.

- Post-Installation and Maintenance: Facility managers are responsible for operating the connected lighting system and for maintaining it. Here is where there is another large gap in the industry that can be filled by the System Integrator approach. The ability to monitor and maintain a network-based connected system is a necessary service to assist facility managers typically not equipped to operate and maintain the network aspects of the connected lighting system. The capability to monitor the health status, power usage and connectivity aspects of the building network stack generates an unprecedented ability to guarantee connected lighting service and predictive maintenance.

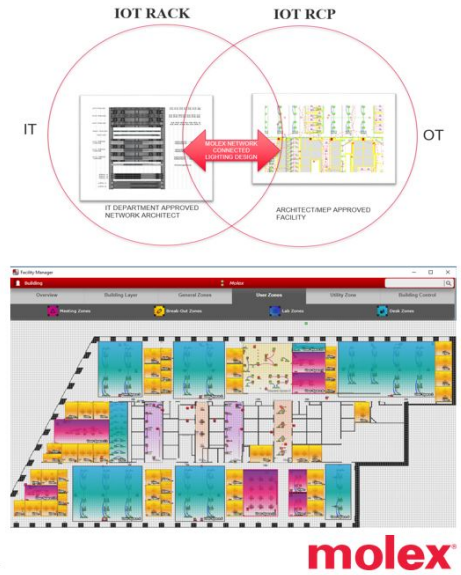

Figure 9: IoT Design: M.E.P. drawings, digital rack and software based digital zones.

Conclusions

Ethernet Based Network Connected Lighting demonstrated the ability to bridge and converge different functions with a single infrastructure as a the foundation for highly integrated buildings. Use cases such as smart scheduling, predictive maintenance, space utilization optimization, bio-dynamic control, and many more are possible using the sensory network nature of connected lighting infrastructure. A structured system integration approach from pre-construction to post installation resulted to be strongly efficient in managing the IoT infrastructure using connected lighting as the natural backbone of the synergistic building.

The Business Case for Sensing – How to be Ready

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Abstract

In this paper, we will examine ways in which the business case for rich sensing in our lights will evolve in a value-adding and logical way, from the current “occupancy only” type of sensing, into progressively more expansive sensor capabilities that will transform both the function and value of our lights. Areas to be examined include:

- The importance and payback for optical sensing within the luminaire to enable closed loop control, performance maintenance and spectral validation
- The progression of capabilities to include measurement and management of bio-active spectra, such as those affecting circadian rhythms and other physiological responses
- How horticultural lighting will pave the way for the incorporation of enhanced spectral sensing in our every-day lighting
- The inflection trigger for environmental sensing in our lights and how it will integrate into the building management strategy
- How to realize value from more detailed presence sensing, the technologies to look for, and the technology trends to watch and be ready for
- The traps to avoid, both in moving too quickly or moving too slowly

We will also address the breadth of sensing technologies that we can eventually expect to see in our lights, including a discussion of how different types of evolving technologies will compete for certain sensing functions, while other technologies may provide multiple functions from a single type of sensor.

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Introduction

There is little argument that lighting is well positioned to serve as the sensing backbone for the Internet of Things (IoT) in our built spaces. Beyond that core fact, the crystal ball gets a bit hazy to tell us when, or perhaps more importantly, how that will really happen. While we all love our technology, recent product introductions in other arenas, such as mobile devices, do tell us that tech just for the sake of tech, may not sell like it used to. There has to be a business case. In the case of IoT for lighting, there has to be a business case for sensing. The lighting industry could just wait until Silicon Valley calls and tells us everything else is connected, and they are just waiting for, but wouldn't it be better to make some profits along the way?

In this paper, we will examine ways in which the business case for rich sensing in our lights will evolve in a value-adding and logical way, from the current "occupancy only" type of sensing, into progressively more expansive sensor capabilities that will transform both the function and value of our lights.

Lighting: The host for the IoT

Too often these days, a technology community can see such an obvious benefit to a technological deployment that it can be difficult to see what the real drawbacks may be. What we want to avoid as an industry is finding ourselves on a path through a minefield littered with cool lighting tech that is in search of customers. This is especially true when it comes to sensing integrated into our lighting systems. One fundamental premise is no doubt true: Lighting is one of the few "must have" features of our built spaces; it is always connected to electricity; and it has a great view of the space. The industry holds to be true a second assumption: Most lighting will be connected. That leads us to suspect a third premise: Lighting is a natural host for the sensing associated with the Internet of Things. While one might try to make a story out of simply connecting the lights and adding sensors, in order for connected lighting to succeed, there has to be a business case for that connectivity and its associated sensing. Fortunately, there are real business cases now and if we understand them, we will leverage those business cases and succeed with enabling lighting to become the key platform for the deployment of the IoT's sensing in our built spaces.

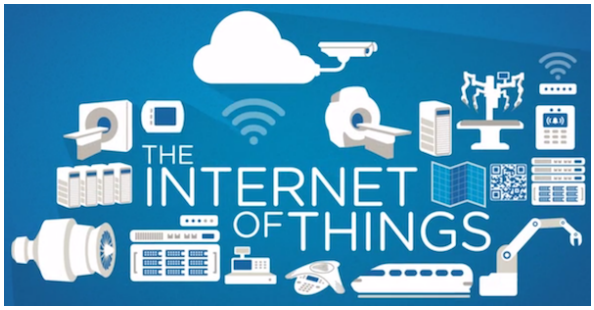

Figure 1: The IoT is a lot of things, but it is not a business case on its own.

One thing we should make clear at the outset, "the IoT" itself is not a business case. The IoT is a platform to deliver a collection of capabilities and services that create the value. The current hype of the IoT is reminiscent of another platform technology which we affectionately still refer to as "the Internet". And while it works largely as promised, we did enjoy a memorable phenomenon called the Dot-Com Bubble, which seemed to be an exciting and profitable technological deployment, right up until it burst. With hindsight being 20/20, we can point at a number of cause and effect relationships, but the one most pertinent to this discussion was that many in the business community mistook the platform for a business case. The Internet enabled applications, but could only sustain its value to the degree that those applications found and delivered value to the customers. Using a baseball analogy, some of those applications, such as Amazon or Google, were home runs. But in the world of value creation, the home runs are more often offset not by small progress "base hits" but by full on failures or "strike outs". With that in mind, we need to all be aware of what is value, and what is hype. Lighting companies do not want to find themselves attached to an IoT-fueled bubble that will inevitably pop.

Tunable white, a natural business case

LEDs gave us truly controllable, and in a sense, "digital" lighting. Beyond on, off and dim we have hue, and with controllable hue comes a host of benefits. At one of end of the spectrum of benefits, we find simple personalization and control. People like to be in control of their environment, and lighting has historically been

difficult, or at least inflexible, when it comes to individualized control. The typical office setting has one size fits all lighting, and if there is a way a dim the space, it can almost be considered advanced! And even if there is dimming, or the ability to turn off a bank or two of lights, good luck finding common agreement on the lighting level. Best to leave the controls off. With our digital LED lighting, the opportunity arises to provide more individual control of the lights. Initially that would be offices, dedicated workspaces and conference rooms, but as we see more embedded control and connectivity, it is easy to see how personalized control will develop. You can't necessarily recruit more employees by installing yet another espresso machine or ping pong table, but how about improving the employee's personal workspace comfort by letting them customize the light in their space. Similarly, a building operator could expect to compete more favorably in leasing their space if the client can not only add some walls, but tailor the lighting.

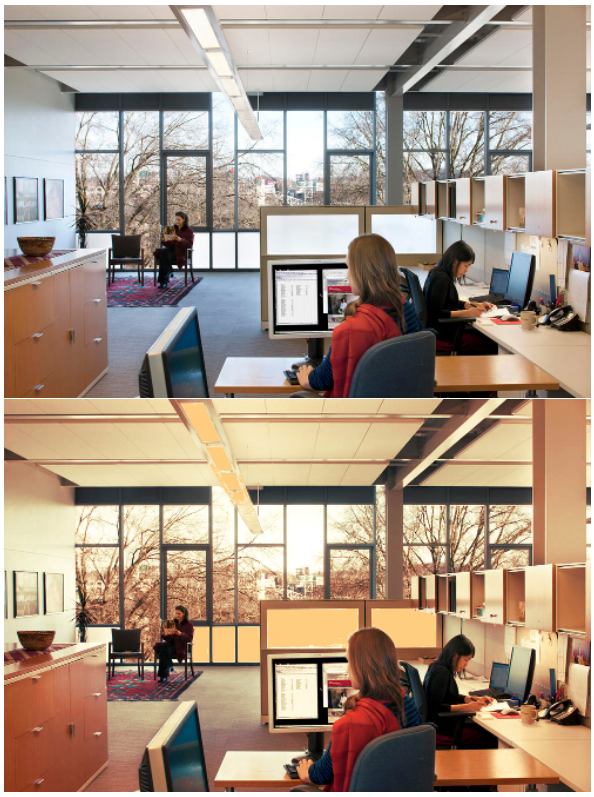

Figure 2: A key initial business case for tunable lighitng is simply personalization and preference.

At the other end of the benefit spectrum are the potential productivity, health and welfare benefits[1]. Whether tunable light can simply help someone feel better, or can serve as an actual prescriptive element towards improved wellness, it will bring value. The simple question right now is this, "If it didn't cost any more than non-tunable light, would you want it?" If more than 50 percent of the time that answer is "Yes!" then we're really just talking about finding the right price point. Will that be 10€ more, or maybe 20€ added to a 100–200€ architectural luminaire? One could contend that with that relatively modest addition to the selling price is all it takes to make some money with tunability, we're close enough to free that there can be substantial adoption. Fortunately, decreases in LED costs have put us in the position where adding more LEDs, a requirement for tunable lights, isn't even close to cost prohibitive. LED costs are now below 1€ per kilo-lumen, which means doubling the number of LEDs in a typical 3000 lumen troffer would only add about 3€ to the bill of materials. If we keep any supporting elements needed for tunable light to a minimum, and do a good job of color quality, this can sell now.

Closed loop optical sensing, bringing the tunable business case to life

LEDs are really good, and they continue to get better. Selection bins continue to narrow and improve, color stability is typically very good, and as light extraction efficiencies continue to trend up, we can incorporate broader spectrum phosphors for improved color rendering without suffering painful efficiency losses. But for all the accuracy and precision LEDs can bring to the party, the human eye is still better. The standard observer model of color recognition tells us that the average person will be able to perceive color differences between lights once they reach 2–3 standard deviations (or MacAdam steps). And those standard deviations are pretty tight. So tight, in fact, that they can be exceeded by component variations that can be measured in just tenths of a percent. In other words, if you take a warm/cool color mixing tunable white type of luminaire, and command the strings to mix at a 40/60 ratio, one light that is delivering that at 40.1/59.9 can be a noticeably different color temperature than one which is at 39.9/60.1. And that assumes that the LED flux bins were accurate or average out to within tenths of a percent as well.

If modern multi-channel digital driver technology, current feedback componentry, precise binning and device characterization and in-factory calibration are all carefully applied, the result can

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combine to deliver a decently precise result on day 1. But that would come at an expected manufactured cost uplift (including characterization and calibration) on the order of about 20–30€, and leaves open the question of how perfect the color of the light will be in 3 or 5 or 7 years down the road. Even the highest quality power system and LED characteristics will change slightly over time and temperature. Mitigating that to some degree with the current feedback and careful power, temperature and lifetime characterization is possible but comes at a cost.

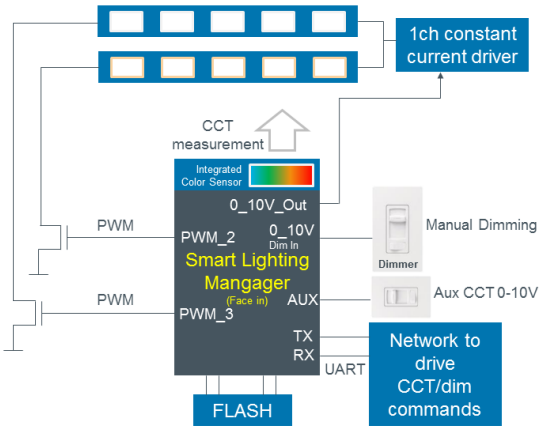

Figure 3: Optically integrated chipscale technologies make tunable light cost-effective now.

The Cost-Effective Solution: Closed loop sensing

There is an answer available today that does open the door to both optimized bills of materials, as well as increased lifetime precision. The cost-effective solution is optically-enabled closed loop sensing. By making use of a properly calibrated CCT or color sensor, specifically one that is not prone to drift over time or temperature, one can greatly slash the overall manufactured system cost of a tunable white luminaire. The addition of closed loop sensor control creates a system approach which simply "looks" at the color of the light and when it sees the light is off target, it commands small adjustments to the LED string currents until the targets are reached. Our eyes are relatively slow and adjustments can be relatively fast, creating a smooth tuning to the target, and then holding it there. If power systems or LEDs drift over time or as operating conditions change, the sensing loop doesn't care about absolute values other than that of the target color point. It just continuously commands a little more here and little less there to hold things on the target.

The implications of this are substantial. Less stringent binning, or LED wider binning selections become available. Since you don't need quite as specific bin sets, on-hand inventories and inventory carrying costs may be able to be lowered. From the power side, lower precision (but still reliable) driver components can be employed, including moving from a multi- to a single-channel power supply and using long-employed current steering techniques. Thermal tolerances can be slightly loosened, saving in both the bulk of the heat sinking as well as the indirect shipping costs of both raw materials and finished goods. Finally, with pre-calibrated sensing elements, light by light calibration at assembly time can likely be eliminated. Any one of these can create a savings that more than pays back for the 3–5€ cost of adding the intelligent closed loop sensing to a tunable white luminaire. But it doesn't stop with tunable white systems.

The same approach can be applied to single CCT luminaires. For instance, if a luminaire is specified at a 3000 K CCT, that CCT could be created using two CCT strings of LEDs to create a mix, say of 2700 K and 3500 K LEDs. Choosing a parts count (total lumen) ratio in which each string is running at 80–85% duty cycle to deliver the initial 100% lumen rating, you have allowed 15–20% headroom to work with in order to slightly shift the mix to maintain exactly 3000 K, as well as to drive a bit more current to maintain lumen output as the LEDs depreciate over time. The result is on-target light, over lifetime, as well as all the cost savings benefits described for the fully tunable lights above.

Building Baby Steps: HVAC and space utilization

From the tunable CCT discussion above, we need to keep in mind that tunability was the application, and sensor-integration is an enabling technology to support a cost effective approach to meeting the demand for tunable solutions. And to tune them you connect to them. Connected lighting comes right along with the business case that drove tunable lighting. So now we're connected.

How we're connected doesn't need to be part of

this specific discussion, since the need for connectivity was bundled in to the demanded application (tunability). Whether it is the addition of 1€ worth of component to make a simple multi-drop serial command channel, or 5€ for a more comprehensive wireless communication protocol, the data-hungry IoT ecosystem is creating those solutions and protocols for us, even if we aren't giving them much back right now.

So we're connected to support tunability, what is the first real step towards becoming part of this IoT thing? The most obvious next-step for add-on sensing in our lights will environmental. Optimizing the HVAC system is a natural energy saver, and the best way to do that is to be able to look at more granular data. Heat or cool where it is need, to the level needed. Efficiency is that simple[4][5]. Adding temperature, humidity or air quality sensing into the lights may not appear to be obvious until one realizes that silicon scale technology has knocked the cost of that kind of sensing down by some orders of magnitude over the last decade or so. For just a few euros added to some percentage of the lights, most likely just one in a normal single or double office, a building could eliminate those 50–100€ boxes on the wall in every room at a substantial savings. And better data comes with it. In the case of the HVAC system, we know what to do with the data, so this isn't a stretch in terms of new data handling or decision making paradigms.

A likely next logical step to manage the efficiency of our spaces beyond the HVAC is presence sensing. This is not to be confused with on/off occupancy sensing, but rather more like people counting. The operating expense equivalent of any space is the efficiency of its usage. If a space is full of productive workers, it is cost effective space. If it is empty, it isn't as cost effective. While space planners try to make every space productive, the reality on the ground can vary as day to day operations and staffs evolve, grow or contract. Unless live usage data for the space is available the actual productivity is a guesstimate. With live data gathering, those responsible for space planning and utilization can find opportunities to optimize the space, and add or consolidate when needed. In some instances, that process can tell a COO that rather than building a new building, they simply need to develop a better utilization strategy and thereby save some millions or tens of millions that are better used for investments or simply flowing to the bottom line.

Presence detection has all the appearances of being the next Wild West for solution development. Passive infrared (PIR) has been one mainstay for detecting human bodies. By expanding from the current single pixel to multi-pixel solutions, a map of the human presence in the space can be created with relative low computing and data overhead. Time of Flight and microwave sensing offer similar opportunities, but will require local pre-processing to transform detection data into the XY coordinates that maps thrive on. Image sensors can provide a lot of available detail on people flow, even if it is formatted to be anonymous or "blobbed" in some way. There can be added cost in terms of processing power for image sensing, but a lot can be accomplished these days with a 1–2€ sensor element combined with a 1€ microprocessor. And remember, tunable lights created a case for connected lights, so the "burden" of the networking hardware has already been borne by those lights. It is literally just a smart-sensor add-on in a cost sense.

Bigger Steps: Productivity enhancements

A standard rule when examining the efficiencies available in our spaces is the "3/30/300 rule". That is a general guideline on the cost of space (in dollars), per square foot, per year for energy, rent and people/payroll (and sorry, it's a dollars thing... but 37/375/3750 per square meter is just harder to crunch).

3/30/300 can better help us rank the efficiency enhancements in terms of return on investment. For example, a 10% increase in energy efficiency results in a typical 30-cent savings per square foot (environmental sensing and the HVAC for instance). A 10 % savings in space utilization saves one $3 per square foot (presence sensing). But with a $300 per foot allocation to people, just a 2% gain in productivity there will equal the combined savings value from 10% better space utilization while somehow zeroing out all energy costs.

Where do we get this productivity gain? From better light. Whether that is healthy days in the office, or a full day's worth of attentiveness instead of the classic afternoon slow-down, better work in the same time means productivity gains. Looking into the not too distant future, we can move

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beyond general well-being or increased user satisfaction that comes from a more controllable lighting system into actual to prescriptive lighting. The leading research topic in this realm is in the area circadian rhythm influence. For many decades, we have been feeding employees "not great" light. Not unpleasant per se, and maybe not extremely damaging on the whole, but certainly not supportive of healthier day to day living. The reference to "day" can be taken explicitly, as once we cross into night, the body of data is building rapidly to support the contention that our lights have been messing up our night time body clocks. This occurs by suppressing that normal late afternoon "wind down" that leads to a healthy sleep cycle[2][3]. This can be more extreme for shift workers, which are getting plenty of attention, both regarding how to minimize the off-cycle disruption, as well as how to maintain both productivity and accuracy of work in what would be normal sleeping times. We're not tackling the body of science here, but for anyone in attendance at lighting industry seminars, the topic is clearly well and deeply covered, and it seems fair to say the research is gaining even more momentum.

Interestingly, if tunable lighting is deployed in a space, the first iterations of more prescriptive light scenarios may simply be a set of lighting transitions and CCT tuning range limitations that correspond to particular times of day (and night) and seasons of the year. Basically, it is just an app added on top of that installed tunable hardware platform. For the lighting control service, it is a potentially substantial value-add if it brings even a small percentage gain to that 300 in our 3/30/300 rule.

The progression of system capabilities from the initial simple transition (scene) approach to more sophisticated prespcriptive spectral "dosing" control can reasonably be expected. To support that, we will see a demand to add-in more integrated spectral sensing to better inform the circadian app by directly measuring total dosing bio-active spectra in the space over the course of the day. One could also predict that there will be a desire to bring those measurements to the individual level, presumably by combining the data from their computer displays, phones and wearables in order to more precisely monitor exposures, as well as the physiological responses to that exposure, in order to tailor the lighting to the individuals under them.

High value areas for this kind of monitoring-control-feedback for lighting versus productivity will include the medical arena, where hospitals can see specific return based on improved patient outcomes as well as reductions in costly mistakes by off-cycle workers, and also in mission critical 24 $\times$ 7 environments, including power control plants, refineries, chemical plants and such where mistakes can not only be costly, but dangerous to masses of people.

As far as the sensing to support this, it is already well available courtesy of our mobile phones, which have been demanding more and more spectral monitoring to enable better management of cameras, associated flash systems, and for display management. Multi-spectral sensing is here, and cost effective, now, but it isn't yet a business case for our lights. For this application set, we'll all just be waiting on the science to suggest what we need to do. Interestingly, as we add spectral data gathering to the space, we'll also be supporting some of the other sensing capabilities. An example might be adding spectral information to the presence sensing (as we watch colors change, we may get a better sense of activity) or we may find that other aspects of air quality can be indicated by the same sensor that is telling us how much 450 nm blue light we have had that day.

Horticulture and special use lighting

No discussion of spectrally controllable lighting would be complete these days without a mention of other cross-pollination opportunities. The most talked-about application for tunable lighting right now is in horticulture, where spectral management holds the promise of better crop yields per square meter, while managing other aspects of plant growth such as nutritional content, disease resistance or post-harvest shelf life. The sensing difference when it comes to horticulture is that it will not be about "the color" of the light, but rather all about the spectral power distribution (SPD). For plants, SPD profiles specific to the type of plant will be implemented to deliver the right kind of light at the right time of day or night to manage towards the desired characteristics. For the human space, SPD influence is pretty much limited to color rendering and any bio-active influences, with the bio-active influences themselves pretty much narrowed to

the body-clock discussion. But it is highly probable that the system solutions that enable us to tune lights to a SPD profile that excites the food plants, will also be applicable to how to efficiently and precisely tune the lights in order to excite the food plant shopper. Whether displaying food or fashion items, we'll begin to understand what generates additional ROI from our tunable lights and there is no doubt we'll take advantage of it.

Conclusion: Taking advantages, avoiding the traps

Hopefully we have put forward a compelling case that with the dramatic reduction in LED cost-per-lumen in just the last few years, tunable lighting is not only a viable business case, but that it can actually be the lead-in for IoT. When specifiers understand that thanks to BOM optimization enabled by closed loop optical management that tunable lighting no longer has to cost 2X the price of non-tunable, but rather more like just 10% more, they will want it. And tunable lights are the first step to connected lighting. And connected lighting opens the coming value-add opportunities for the luminaire manufacturers, including environmental, presence and eventually, prescriptive spectrum lighting.

To take advantage of that, luminaire manufactures need to move now to mainstream tunable lighting. The mistake will be assuming it is "specialized" and attempting to price it as a high-value/high-margin feature addition. With silicon-scale technologies, it can be both inexpensive and better than it is now in one single step. Those that grab this will take market share, rapidly, while also kicking off the new paradigm that LED lighting is no longer about being cheaper from generation to generation (the trap) but that it is now about adding value from generation to generation.

Beyond the mistake of moving too slowly into the tunable lighting, the other pitfall to avoid is moving too rapidly into IoT lighting. Customers don't know what to do with the data yet, and luminaire manufacturers don't either. That ecosystem and landscape will shape up over the next 3–5 years, but even as it does, the IoT is still not a business case for lighting. It is a platform that will support the continued increases in value-add that sensor-equipped, application-enabled lighting will bring forward-thinking luminaire manufacturers. Yes, add environmental sensors as soon as you have connectivity to the building management system. But after that, instead of throwing out a precises step by step plan now, read the field and react to actual developments. Most likely the sequence will be to add presence as the BMS is enhanced with space planning and tracking, followed by more sophisticated spectral and presence capabilities. In every case, keep it firmly in perspective that "the app" is the business case, and our job as an industry is to deliver the right sensor driven lighting as the enabler.

References

[1] Co-Chairs: Brian Liebel, IES and Robert Karlicek,Center for Lighting Enabled Systems & Applications. *Transforming Healthcare and Wellbeing through Lighting Workshop Report* (A definitive topic summary with numerous additional published paper citations) https://lesa.rpi.edu/wp-content/uploads/2018/02/Transforming-Healthcare-Wellbeing-through-Lighting-Workshop-Report.pdf. IES Annual Conference October 2016.

[2] Jessica Schmerler *Q&A: Why Is Blue Light before Bedtime Bad for Sleep? Two neuroscientists discuss how blue light negatively affects health and sleep patterns.* (Simple introduction of circadian/lighting relationship issues) https://www.scientificamerican.com/article/q-a-why-is-blue-light-before-bedtime-bad-for-sleep/ September, 2015

[3] Emily Laber-Warren, Scientific American Mind *Out of Sync: How Modern Lifestyles Scramble the Body's Rhythms.* [*Digital devices and 24/7 lifestyles are messing with our body's natural rhythms, threatening our health*] https://www.scientificamerican.com/article/out-of-sync-how-modern-lifestyles-scramble-the-body-s-rhythms/ September 2015

[4] Gerhard P. Hancke, Bruno de Carvalho e Silva, Gerhard P. Hancke Jr. *The Role of Advanced Sensing in Smart Cities.* Sensors 2013, 13(1), 393–425; doi:10.3390/s130100393 http://www.mdpi.com/1424-8220/13/1/393/htm

[5] Daniel Minoli, Kazem Sohraby, Benedict Occhiogrosso *IoT Considerations, Requirements, and Architectures for Smart Buildings—Energy Optimization and Next-Generation Building Management Systems.* IEEE Internet of Things Journal. Volume: 4, Issue: 1, Feb. 2017 https://ieeexplore.ieee.org/abstract/document/7805265/

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Professional Lighting between Vision and Reality

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Abstract

The whole world is talking about smart lighting and the lighting industry is in the middle of a major transition. But first let's take a look at other industries and technological trends. Back in the early '60s, film makers promoted futuristic ideas that ranged from fingerprint sensors right up to person- or car-tracking systems. The '80s brought the first PCs and the '90s delivered WiFi™ and Bluetooth® technology.

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Introduction

By now, beaconing has become commonplace and fingerprint sensors have already been superseded by face unlock systems. The year 2014 then saw the launch of Google Glass, an innovative wearable whose ultimate failure was probably due to it being too far ahead of its time. And while the industry is not quite there yet, the smart contact lens as well as voice and gesture control systems are set to hit the market sooner rather than later. After all, 10 years ago who would have thought we'd all be walking around carrying a glass-and-aluminium gadget called a smartphone?

Robots constitute another human dream and have long since ceased to be only the stuff of which science fiction is made. As an example, the US American government spends around US $60 billion per year, or about 10% of the defence budget, on robotics and artificial intelligence (AI). At the same time, the adult entertainment industry is busy creating so-called love bots that promise to become ever more "humanised" as time goes by.

A personal home bot that will do the cooking and cleaning for you may well take a while longer to appear on high street shelves, but the next 10 years are already likely to bring radical changes to life as we know it today.

But back to the lighting industry and the topic of whether 1200 bit/s DALI is truly future-proof?

To many people, lighting control systems seem to be a little like magic, to a point where some are now touting the lighting industry to be in pole position with regard to IoT for buildings due to the fact that we use mains power in ceilings. Another work of magic? And people tend to talk about added value — but without specifying what this added value actually is. But even if we do succeed in finding out, will this added value be something we can sell?

Indoor navigation, asset tracking, beaconing, smart metering — without doubt, these are not DALI applications any more. Perhaps the reanimated DiiA DALI PMD proposal will be capable of rescuing DALI as a door opener to IoT? Only the future will tell.

If asked for now much longer DALI is likely to survive, my answer would be for a few years to come, maybe less but possibly more if DALI PMD can succeed in delaying the demise of the standard. But the question of whether it is worth investing part of your development budget in DALI is one you'll have to answer yourself.

So if DALI looks set to die out, is IoT the way forward? But what exactly is IoT and what new global protocol will establish itself? A new alliance pops up every day that serves to make the protocol jungle ever denser, or rather make the global protocol war ever fiercer. Who has the time to keep abreast of all of these daily developments? Or yet be a part of every alliance?While much talk currently centres around protocols, specifications and interoperability, it is not the actual protocol itself but rather the application layer that is key for our lighting solutions. Care should be taken in waging the protocol war since it wastes resources and will deliver neither any winners, nor a global standard. It would make more sense to focus on the application instead.

So what do we want, what's our vision for the future? There is no doubt that smart lighting is set to change the future — but how do we get there? One thing is clear, the future of lighting is wireless.

Could Bluetooth® MESH or WiFi™ MESH provide the answer? Perhaps. But it is equally possible that WiFi™ and Bluetooth® will (have to) give way to RedShoe MESH in five years' time. Even if you do not believe that will happen, it is my belief that it is at least a possibility that should be taken into consideration. My suggestion would be to shift the focus from the transportation layer to the application you'd like to create and whether you can do it by yourself.

So which real-life opportunities does the immediate future hold?

Based on Bluetooth®, VS has created the open Blu2Light MESH network with a clear focus on the application layer needed within the lighting industry. Why Bluetooth®? Because we believe it to be the best medium for open-device communication for the coming years.

From a technical point of view, the differences to other mesh solutions are as follows:

First, a single mesh network could be equipped with a minimum of 250 Bluetooth® devices — a number that could even be exceeded if necessary in the future. And it comes with all standard features like OTA updates for the mesh and application parts.

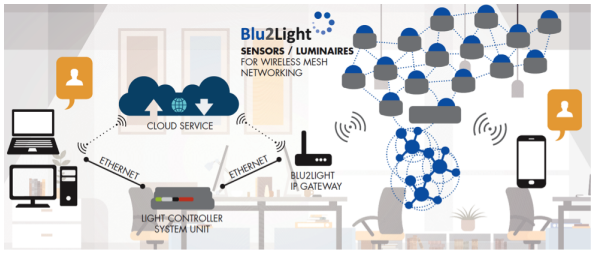

Figure 1: Blu2Light system overview.

Although Bluetooth® offers 40 communication channels, the official SIG MESH uses only 3 channels with a flooding mechanism. It is therefore possible to improve both data security and increase data volumes in the mesh. As a result, the Blu2Light mesh see Figure 2 uses all 40 Bluetooth® channels with a combination of routing and flooding mechanisms to ensure best performance. In addition, the self-healing mesh works like an organic cloud see Figure 4 in the background.

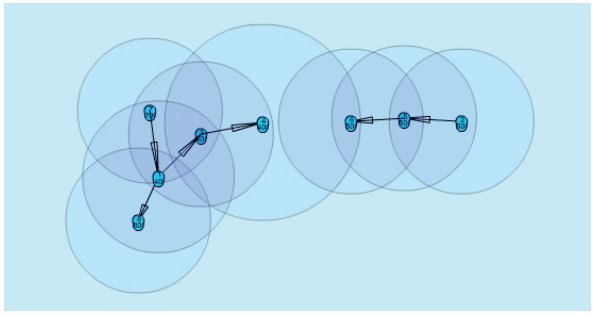

Figure 2: Blu2Light — mesh.

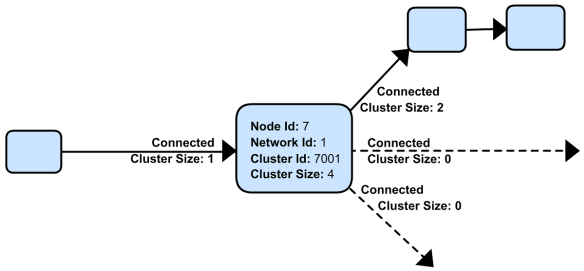

Figure 3: Blu2Light node.

Second, let's take a look at network security. Most solutions are wide open during commissioning, leaving them vulnerable to hacker attacks on

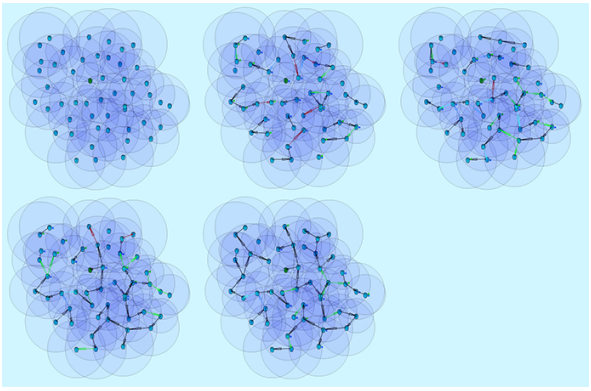

Figure 4: Blu2Light — clustering.

devices or luminaires before final commissioning is completed. Blu2Light devices therefore come with a unique QR code that must be scanned using the commissioning APP on site. In addition, the Blu2Light mesh also features the usual security layer plus internal mechanisms against network hacking and spamming. Thanks to this multilayer security concept, the VS Bluetooth® mesh offers superior protection against external hacker attacks.

But all these network capabilities and security features are nothing without the application. To facilitate a practical solution for building and lighting applications, we therefore created a neutral platform that we named "System Luminaire". At this level, all devices are equal and provided the optional hardware is in place, DALI, DMX or 0–10 V devices are also connected or linked up during the commissioning process, giving you maximum flexibility to connect existing devices as well. And even DALI will be supported with DT8.

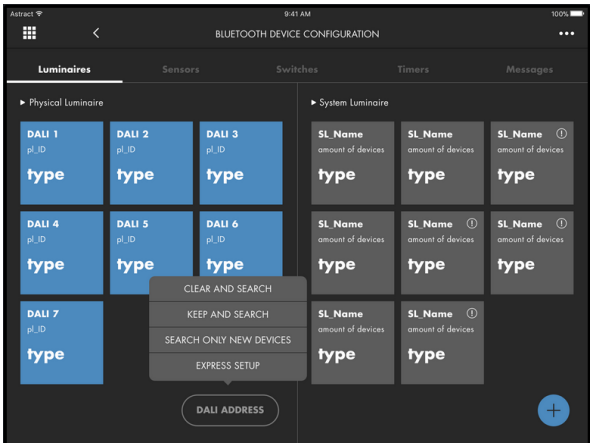

Figure 5: Blu2Light — system luminaire configuration.

Best of all, as a standalone system, either within the mesh or connected to the cloud, it works

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automatically without needing control commands from a central controller. Devices thus interact based on actions and reactions in the manner of decentralised intelligence.

The standard application even includes time switching, colour controls and beacon messaging, e.g., Figure 6.

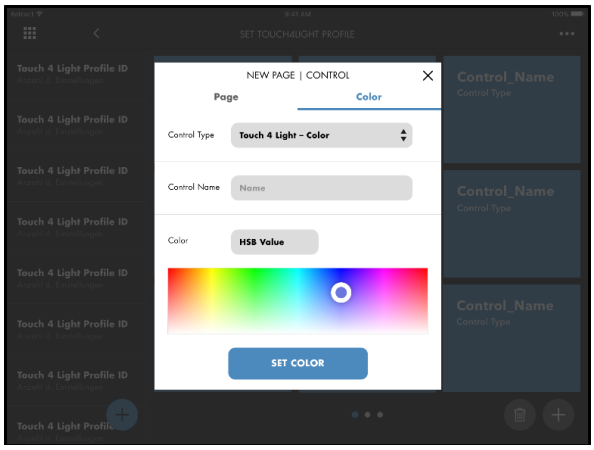

Figure 6: Blu2Light — colour control.

But the protocol is equally suitable for integration into facility management systems such as blind or audio controls.

And finally the system can be used with any cloud service in the world, meaning that customers can use their own cloud service or the cloud provider they trust the most.

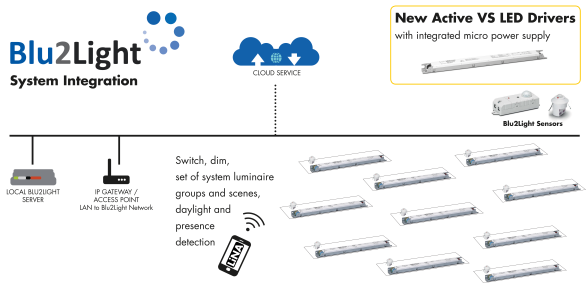

Figure 7: Blu2Light — system integration / cloud service.

Conclusions

The invitation is clear: let's work together to find solutions and not focus only on protocols.

The time is rife for more collaboration and less rivalry within the lighting industry. Joining forces will let us advance closer to that coveted pole position and create the turnover we all need for our companies not just to survive, but thrive.

Horticultural LED Lighting Market, Industry and Technology Trends

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Abstract

The horticultural lighting market's current boom is driven mostly by greenhouse applications, for which artificial lighting is used to compensate for natural light variations and increase production yield. But greenhouse applications represent only the tip of the iceberg in this business, and new applications, mainly driven by urban farming, are likely to make the horticultural lighting market boom in the mid/long-term. In this context, we estimate the 2017 horticultural lighting market (i.e., system level) to represent a business of 3.8B dollars. And it should grow to more than 8B dollars in 2022, driven by the transition to LED technology and the emergence of new applications. But this is only a starting point. Indeed, indoor/vertical farms are poised to boom from 2022–2027, propelling the total market to more than 17B dollars in 2027. Such trend is likely to have an impact on the industry as LED technology act as a game changer. In a global lighting market that is becoming increasingly competitive, horticultural lighting is seen by the LED lighting industry as a new opportunity for which to develop high added-value products and reap greater margin levels. However, established LED players also face competition from new entrants (mostly start-ups and SMEs) desiring their own share of this growing opportunity.

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Why using grow light?

Use of grow light is mostly driven by societal and environmental issues.

Societal issues: Global population has doubled since 1970 to nearly 7 billion people today, and will reach 9 billion people by 2050.Feeding this population would require raising overall food production by 60%. In this context, we need therefore to produce more food for human and animal consumption, to have more arable land to produce this food (. . .), and without causing negative environmental impact. Additionally, population is having more requirements on food (e.g., fresh food, local production. . .). Consequently, we have to increase the productivity of agriculture wand bring it to regions where it is not possible by traditional cultivation methods.

Environmental issues: On one hand, productivity might be affected by climate changes issues, like insects and pests, climate uncertainty, new year-round production (and you can get tomatoes in winter. . .). On the other hand, lack of available arable land in urbanized area makes conventional agriculture not compatible with new requirements about pollution and healthy production wishes. One solution to these problems is to control the growing environment of plants in order to give protection against pollution, insects and climate uncertainty and to increase productivity. This control should be profitable for producers and farmers to be applied in large scale.

Using artificial light might allow to help solving those issues by being able to control the quantity of light, its quality and durations of photoperiod.

New applications will drive a horticultural lighting revolution

The horticultural lighting market's current boom is driven mostly by greenhouse applications, for which artificial lighting is used to compensate for natural light variations and increase production yield. For these applications, traditional light sources like fluorescent and high-pressure sodium (HPS) lamps are currently the most popular solutions. However, LED technology is catching up and recent developments have allowed the technology to enter the horticultural lighting market. LED's primary advantage is its low power consumption compared to incumbent technologies, which allows for a lower energy cost. Also, LED-based systems produce less heat, which allows for inter-lighting: LED luminaires can be placed near a lower layer of plants that are usually shaded from light by the upper layer, and increase their production consistency, or yield.

Greenhouse applications represent only the tip of the iceberg in this business, and new applications, mainly driven by urban farming, are likely to make the horticultural lighting market boom in the mid/long-term. Nowadays, arable land is usually far from big cities and metropolises with millions of people. And as consumers become more conscious of how and where their food is produced, farmers are finding it more difficult to keep up with urban growth. City farming represents a potential solution to handle these needs and challenges by allowing for the growth of plants, fruits, and vegetables in a confined environment, on multiple layers (to maximize production), and without sunlight (i.e., using only artificial light).

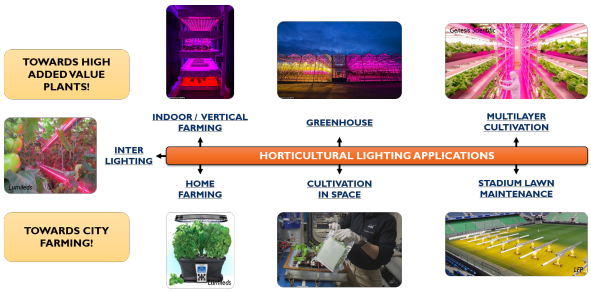

Figure 1: Horticultural Lighting Applications.

In the short-term, these new indoor horticultural applications (and their related industries) are likely to emerge within the culture surrounding high added-value plants (i.e., medicinal plants). A perfect example is the flourishing medicinal cannabis business in North America, which has sparked the emergence of innumerable companies dedicated to this culture. However, urban farming will not be limited to just high-end products — in fact, several urban/vertical farms are already being developed in different parts of the world to produce common vegetables like radishes, lettuce, and basil.

By 2022, a potential market opportunity of more than 8.5 billion dollars at system level

The 2016 horticultural lighting market (i.e., system level) represented a business of nearly $3.1B, which should grow to nearly $3.8B in 2017. The current business is mostly driven by greenhouse applications (~92% in 2017) and incumbent technologies (~79% in 2017), but a transition to LED technology and the emergence of new applications will further increase this market's size and attractiveness, both at system and LED device levels. In this context, we expect the horticultural lighting market to reach nearly $8.6B in 2022 (at a CAGR of 17.8%) — but this is only a starting point. Indoor/vertical farms are poised to boom from 2022–2027, propelling the total market to more than $17B in 2027.

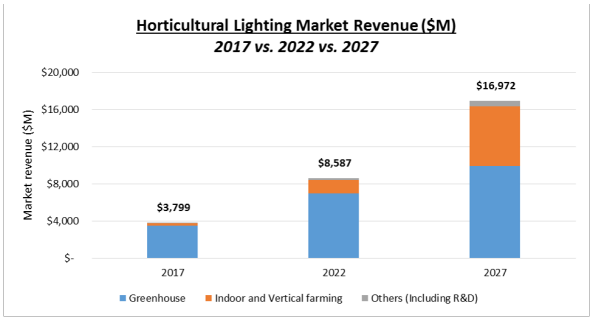

Figure 2: Horticultural Lighting Market Revenue.

At the LED device level, market opportunity represents ~$100M in 2017 and should grow to ~$400M in 2022 (potentially reaching $700M in 2027).

Led technology: a potential game-changer in the horticultural lighting industry

In a global lighting market that is becoming increasingly competitive, horticultural lighting is seen by the LED lighting industry as a new opportunity for which to develop high added-value products and reap greater margin levels. However, established LED players also face competition from new entrants (mostly start-ups and SMEs) desiring their own share of this growing opportunity.

As of Q4/2017, the LED horticultural lighting industry is still small, with less than 50 players identified as offering dedicated LED-based systems. The industry is highly concentrated in North America (50%), the result of medicinal cannabis's legalization.

Looking ahead, industry evolution will strongly depend on market dynamics. Indeed, industrial players' marketing and communications are currently focused on two main applications:

- Medicinal plants (mostly cannabis) production, which is today the main market driver
- Vegetable production, which is developing with a "low-end / high-volume products" focus

Part of the established lighting system industry may never proceed (at least visibly) with the first application (medicinal plants), in order to preserve brand reputation. Such a situation is likely to benefit new entrants that will generate revenue swiftly and rapidly increase their horticultural lighting market expertise.

At the device level, most LED manufacturers embrace a "technology push strategy", taking advantage of their traditional LED portfolio (i.e., UV, visible, and NIR LEDs) to quickly offer some horticultural lighting solutions and related marketing tools, such as dedicated datasheets. In the future, with a better understanding of LED light's effect on plant growth, these players might start offering more dedicated solutions (i.e., fine-tuned wavelength package, multiple wavelength package, etc.).

The missing block in the supply chain is mostly at the module level, with no real supplier in 2017 — reason being that the market is still emerging and the industry is still young, with no standards and regulations. In this context, each lighting system manufacturer design its own module with a specific wavelength mix/recipe.

Some companies are finally starting to position themselves as solution providers, offering not only lighting systems but global solutions integrating sensors (humidity, oxygen, etc.) and data management software. The objective of these smart lighting systems is to further increase the productivity of greenhouses and urban farms.

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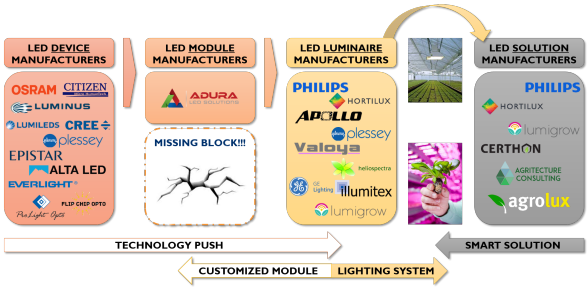

Figure 3: Horticultural Lighting Supply Chain.

Conclusions

Light is key in providing the necessary energy to make plants grow, flowers bloom, or seeds germinate. Artificial light can provide a supplementary amount of energy in areas where natural light is not sufficient, and is commonly used in greenhouses. Many different effects can be observed on plants depending on the type of artificial light being used (spectrum).

So far, conventional light sources were mainly used for horticultural lighting: high pressure sodium, metal halide, fluorescent. Those sources had the advantage of providing a significant amount of energy in order to bring supplemental lighting where it is needed. However, it had the disadvantages of requiring frequent maintenance, and of not being fully optimized for plant needs. Such technologies also consume a lot of energy and provide heat that needs to be extracted from the installation.

The development of LED technology brings a new paradigm to the horticulture market as it offers unprecedent possibilities of supplying efficient and effective energy to plants where-ever required. LED's allow full control of the light spectrum, intensity, and beam, to perfectly match needs of plants. LED will also dramatically reduce investments and maintenance costs thanks to price decreases and long lifetime.

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Lighting Technology Trends

76 Repro-light: Modularity, Sustainability & Personalization for the Lighting Industry
by Dr. Katrin Tanzer, Bartenbach GmbH

84 Zhaga: The LpS 2018 Update
by Dr. Dee Denteneer, The Zhaga Consortium

94 Lighting Goes Smart — Should We Care About Cybersecurity?
by Dipl. Math. Alexander W. Koehler, UL

102 Metameric Circadian Lighting: A Technology Analysis
by Tamara Aderneuer, CSEM Center Muttenz

108 How Digital Lighting Will Further Revolutionize Automotive Lighting
by Pierrick Boulay, Yole Développement

112 How to Solve Increasing Challenges in LED Luminaire Production
by Markus Spiekermann, BJB GmbH & Co. KG

118 Can the Success of OLED Displays be Transferred to Lighting?
by Dr. J. Norman Bardsley, Bardsley Consulting

124 Total Lighting Efficiency: Think Outside of the Chip
by Tom Veenstra, Innotec

134 The Technology and Implementation of Dynamic Beam Shaping
by David Kriebel, LensVector

Repro-light: Modularity, Sustainability & Personalization for the Lighting Industry

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Abstract

The goal of the project Repro-light (“Re-usable and Re-configurable parts for sustainable LED-based lighting systems”) is to initiate a transformation in the European lighting industry towards a circular economy. Through the development of an intelligent LED-based luminaire with modular, stackable architecture the project seeks to change the industry’s view of the LED luminaire into a customized, sustainable product with hight functional value. To determine the architecture of such a luminaire and the requirements for from the different stakeholders (e.g., end-users, customers, facility managers) a user-centered design-approach is taken. Questionnaires for end-users and other stakeholders have been distributed and focus groups were performed. First results of this approach are discussed as well as the challenges and chances of a modular luminaire architecture.

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Introduction

Repro-light is a Horizon2020 funded project coordinated by Bartenbach with consortium members from the lighting industry as well as sustainability and technology acceptance experts (Figure 1). Running from 2017 to 2020 we want to think about the future of lighting by collecting the requirements of all stakeholders, develop innovative luminaire designs and optimize production for customizable luminaires.

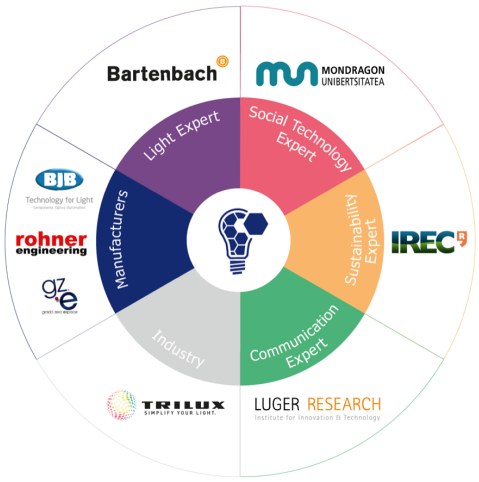

Figure 1: The Repro-light Consortium.

The luminaire should be easily re-configured by all stakeholders involved and the product should be updateable in a way that obsolescence can be avoided. The Repro-light luminaire should be conceived to influence the customer's well-being and health positively. It should also be able to adapt individually to the customer's needs, e.g., the end-user's age or chronotype.

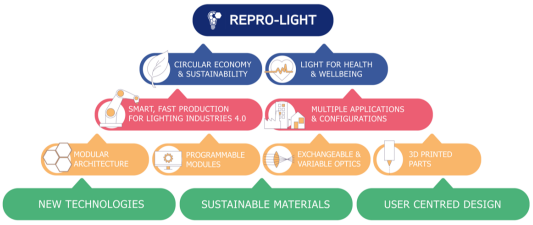

Figure 2: The Repro-light project.

The project is based on 3 pillars (Figure 2). **New Technologies** will be used to develop the modular architecture. This is necessary to allow the exchangeability of the modules, e.g., optics or LED modules, and the inclusion of 3D printed parts. A stackable architecture will allow for a fast and automated production in the spirit of Industry 4.0. The luminaire will be programmable in order to manufacture equal parts in high quantities first and enable differentiation at late stages in the production by software. Furthermore, the luminaire can then later be updated by the user. In that way, it is ensured that the product is suitable for multiple applications and offers enough configurations to be tailored to the individual wishes and preferences.

Through the possibility of updatability and re-configuration we want to avoid the programmed obsolescence of the LED luminaire and in that way make it more **sustainable**. With the inclusion of Life Cycle Assessment and following eco-design guidelines, e.g evaluation and integration of new materials, the most effective solution also in terms of elongation of lifetime and reduction of the environmental impact will be created.

The third pillar is a **user-centered design** approach. The luminaire should satisfy the users' needs at an individual level and maximize their well-being in the workplace. Therefore, the users are included to determine the requirements in terms of personalization, visual and non-visual performance and technology (e.g., which parts of the luminaire should be exchangeable by which stakeholder). Furthermore, a Technology Acceptance Model is used to ensure that the users will accept and rapidly adopt the new technology [6].

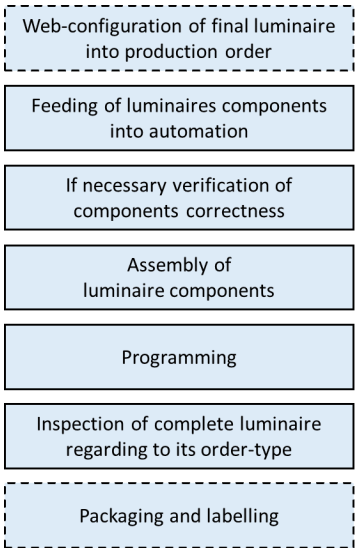

Figure 3: General production processes of luminaires for continuous line lighting, dotted boxes are optional.

The Idea of the Modular Luminaire

Building Blocks for Lighting

The main driver behind a modular and configurable luminaire is the wish to have a mass-produced product portfolio that can be more personalized and diversified. The market has shifted more and more towards individualization over the whole product range — a trend which can also be seen in the lighting industry. Therefore, also the luminaire production must be optimized to enable fast manufacturing and the assembly and configuration of complex and individualized products.

This is important because usually, when a company offers a standardized product in high quantities, then from a production point of view it makes sense to automate the production process. However, when a company offers a highly customizable product in smaller quantities going for an automated production is not really economical. As normally automated production systems have only a limited capability to react to changes in products and used components it is not the most suitable system for highly customizable products. To conclude from this, the requirements for automated production are highly dependent on how the final product of the project will look like and in which degree this product will be standardized or customizable.

The Repro-light luminaire will be developed in a modular way where the modules can be programmed to their intended purpose — allowing for a seamless integration into Industry 4.0. In that way equal parts can be manufactured in high quantities at first and differentiation will only take place in the last stages of production by software, allowing for more flexibility and reduced time to market (Figure 3).

From Automation to Personalization

Personalization is currently discussed an an opportunity for future differentiation in the lighting industry. However, due to the novelty and the value and lack of experience in dealing with this topic, the strategies currently in place are still largely in an exploratory phase and the associated requirements have not yet been defined.

For standard light products end-users have no direct influence on actual product development or functionality, while product development and design are related to human needs. In contrast to customized and personalized lighting products, standard products follow highly specialized target specifications. They are precisely tailored to their application. As a result, product spectra of several competitive products exist, from which the end-user can freely choose. User needs are considered only insofar as they may be included in the target specifications (Figure 4). In terms of production, the value of standard products is usually generated only once by selling the product.

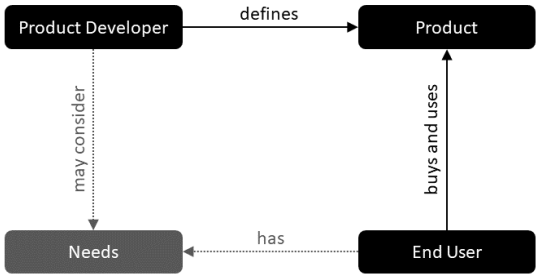

Figure 4: Standard Product Development Cycle.

In lighting, **automatization** has become possible with the development of LED technology. It can be executed as independent lighting control or as integration in higher-level building automation. User needs can therefore be included in the automatization as modulating parameters, but they do not necessarily have to be.

The strong application-specific differentiation of standard lighting products is an advantage and at the same time a disadvantage for the development of lighting products. On the one hand, it allows a target-oriented development and tailor-made functionality of the products. On the other hand, it is forcing companies to constantly re-develop luminaires when product requirements change. These changing requirements result in the concept of **customization**.

Customization allows to create product designs that can be adapted to meet different needs while reducing development time and costs in manufacturing. However, customizable products no longer follow precisely specified targets. Rather, they aim at creating as much freedom for product design as possible (by means of their adaptability) in order to meet the individual requirements of customers [2]. Customization thus results as a “state-of-the-art production

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paradigm" that "aims at producing individualized, highly variant products and services with almost mass production costs" [3].

The adaptability of the lighting products is enabled by a modular design, whose modules can be added or changed. However, in contrast to a modular manufacturing process, the end customer may choose the modules. He is allowed to choose from a predefined pool of available modules and thereby create a product suitable for his individual requirements. To ensure the functionality of the resulting products, the development of predefined interfaces is a prerequisite.

However, in the field of developing customizable products, the number of customizable parameters (modules) influences the complexity of creating the product. This can be a deterrent for customers and is called "mass confusion" [4]. Therefore it is necessary to provide easy-to-use toolkits (e.g., product configurators). They put the end-user in the position to configure products with minimal knowledge.To re-capitalize the above (Figure 5), customized lighting products are primarily defined by user decisions.

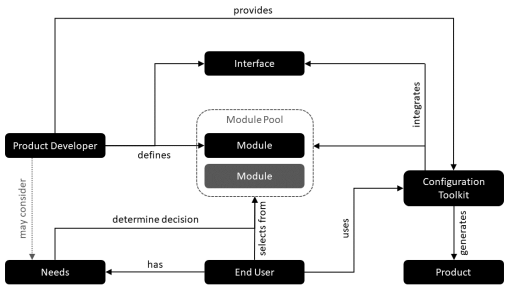

Figure 5: Customized Product Cycle.

The problem of mass confusion plays a crucial role in the context of product individualization. Especially in the service sector, the high degree of complexity and the lack of understanding of the end user needs exacerbate a simple implementation of customization concepts. **Personalization** technologies can help to alleviate these challenges of customization as they allow to support customers in specifying products and services that fit their wishes and needs in a fashion where decision and interaction efforts with systems are significantly reduced [3].

Basically, personalization is considered as the ability to tailor content of services based on information about users' specific wishes, needs and preferences. In this regard, personalized products are generically developed and provide unsupervised algorithms for decision-making. The necessary user information is collected directly from the systems and can also be used directly on site. Thus, the information gathered does not necessarily have to be available to the developing and producing company, which enforces data security and anonymity (Figure 6).

Algorithms for personalized lighting have to reflect the uniqueness of personalities and also have to prove themselves as context-dependent — reflecting not only individual characteristics but also current environmental conditions. The underlying knowledge base therefore becomes large and complex and algorithms for the implementation of personalized lighting are therefore not yet available or very limited.

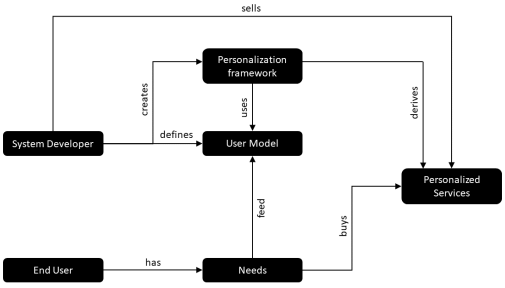

Figure 6: Personalized Product Cycle.

End-Users always try to maintain their comfort in the simplest way while being reactive to externally occurring events, which leads to overcompensation in their behaviour. They make settings that aim to prevent the worst case conditions and react to current stimuli without predicting long-term effects. Personalized lighting control strategies aim to circumvent these issues and provide system-level adjustments for the user's benefits . This will ensure higher acceptance rates and create opportunities for new data-driven markets and services.

Requirements for Personalized Lighting — User-centered approach

As the user's needs are essential for customized and personalized products, the Repro-light project exhibits a user-centered approach to include all stakeholders, but especially also the end-users in a co-creation of the Repro-light luminaire. Several different methods were used to determine the

requirements for a customizable luminaire, among them 5 focus groups with specially selected participants and an end-user survey that was answered by more than 1000 persons all over Europe.

Focus Groups

A focus group is a research method in which specially selected participants are instructed to develop ideas. In a focus group the target is to define requirements for a product or service and to generate new concepts for new developments in an open brainstorming. As a method, focus groups are often performed at an early stage in the development of a product or service. In contrast to individual interviews, the participants are given the opportunity to interact and stimulate each other while discussing and considering ideas and perspectives on a specific topic.

For the generation of novel concepts for modular luminaires, the Repro-light consortium carried out a total of five focus groups with end-users, light planners, luminaire developers, customers, installers and facility managers to involve members of the entire value chain.

Figure 7: Focus groups in different creative phases.

The presence of different professional groups from the lighting sector has led to diverse replies concerning modular luminaires and personalized lighting. As a general observation, it was found in all focus groups that the topic of sustainability and circular economy at the moment receives little attention in the daily business. However, exchangeable modules for longer lifetime have been rated **useful**, especially for the installers, customers and facility managers. In combination with analysis and monitoring services based on sensors and communication modules, this enables new and interesting maintenance services. It was an interesting trend to notice, that developers generally had a more critical view of a modular and customizable luminaire, seeing mostly the barriers and technical difficulties, while the installers and customers saw the benefit and appreciated the idea. The planners were divided in their views. On one hand they could see the advantage in not being dependent on plans anymore and having more flexibility in **adapting the luminaires in situ** if it was required. On the other hand it was discussed how the role of the light planner might change with modular luminaires and their job profile might evolve.

The majority of the focus groups mentioned that they see **great benefits in personalized lighting**, as long as the data collection and protection are in accordance with privacy policy. It was also noted that individual light intervention algorithms must be based on scientifically sound research results (biological effects of light, non-visual and visual effects of light). In all focus groups it was mentioned that there was a risk of losing design aspects and the importance of luminaire aesthetics could decrease when developing modular luminaires in a one-fits-all approach. This could be avoided by giving the customers and end-users the ability to create individual luminaire housings.

Most participants in the focus groups were in agreement that the customer or end-user should adapt at little as possible physically. Generally, an adaption via software is favoured by all the stakeholders [5].

End-User Survey

An end-user survey was compiled by Bartenbach and Mondragon University to gain insight into the end-users' acceptance of their current workplace lighting and their opinions about personalized lighting systems. The survey was answered by more than 1000 end-users from the applications office and industry. Most participants came from Germany, Austria, Spain and Italy. For the analysis of categorical data cross-tables were created and the Pearson Chi-Square test was used with a significance level was of $p < 0.05$.

In the end-user survey we found that the majority of responders were **not content with their workplace lighting** and would like to have it improved (Figure 8). We found that significantly more women want to have their workplace lighting improved and that the older the workers are, the greater their wish for workplace improvement is. End-Users with regular hours and fixed working places are substantially less satisfied with their workplace lighting than people often changing

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work places or having different working hours, e.g., shift work.

We also consistently found that high visual requirements are a driving factor in the wish for an improved workplace lighting. Workers who state they have high visual requirements at work are consistently more aware of light quality and have higher demands for their lighting not only in terms of brightness, but also lighting control and personalization.

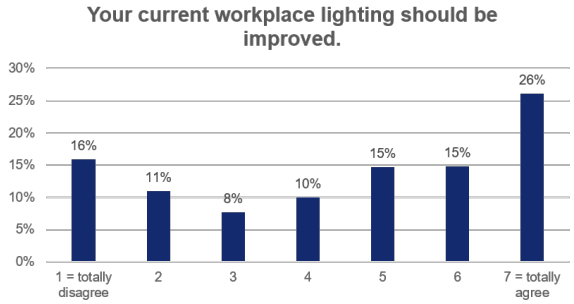

Figure 8: 56% of all end users tend to have their workplace lighting improved.

A striking result that we found is that the believe in the **impact of lighting** is already widespread. No question of the questionnaire received such unambiguous answers as the question if the end-users believe that lighting can impact their performance, their mood and their vigilance (Figure 9). 79% of all end-users state that the colour of their workplace lighting should change when its dark outside. These ratings were even higher for people who believe that lighting can impact their mood and vigilance — the responders who do not believe that were undecided whether the color should change or not.

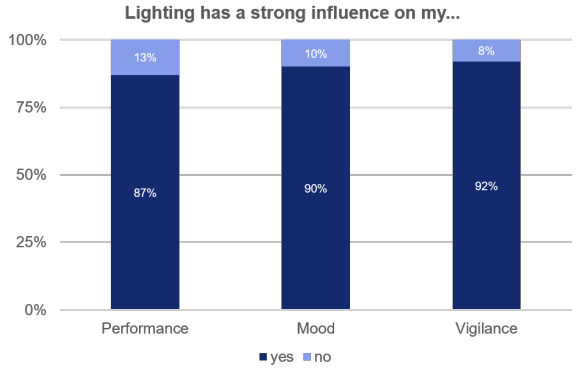

Figure 9: An overwhelming majority of end-users believes that lighting has an influence on their performance, mood and vigilance.

When the end-users were asked which **parameters** of their workplace lighting they would like to change brightness (86%) and light colour (70%) were the preferred choices (Figure 10). However, more than half of the end-users also would like to be able to change the lit area on their workplace. End-Users who can currently not change their workplace lighting are significantly more satisfied with changing just one parameter of the lighting than the rest of the end-users.

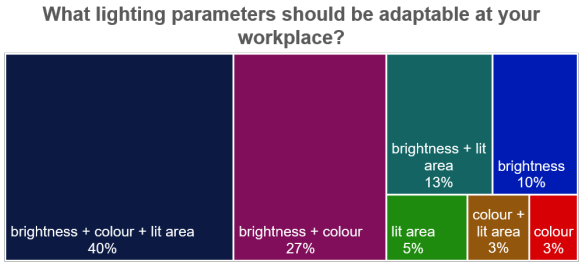

Figure 10: The combinations the end-users preferred when asked which parameters of their workplace lighting they would like to change.

We can see that the workplace lighting improvement is not only driven by the want for brighter or higher quality lighting but also motivated by the light control. 45% of all end-users who control their workplace lighting with an electronic device (e.g., tablet, smart phone) “totally disagree” that they want to have their workplace lighting improved compared to end-users that use switches or cannot change their workplace lighting, where only less than 10% disagree. Already the control with a dimmer makes the rate go up to 25%.

A trend that we could observe throughout the whole questionnaire is an **accustoming and a step-by-step effect**. For example, end-users who currently cannot control their lighting at all would like to change their lighting with dimmers. End-users with dimmers would like to have electronic devices. End-users with electronic devices are rather content with their workplace lighting and are at the same time open to new control strategies such as speech or gesture command, automatic and personalized lighting. In the same way, people who currently have problems with their lighting control are hesitant about changing too many parameters of their lighting. End-users who can currently already adjust the workplace lighting to their personal preferences overwhelmingly think that their workplace lighting should be changed with varying working activities. End-users who are currently not able to do that agree to a significantly lesser extent (Figure 11).

Age also plays a significant factor in almost all

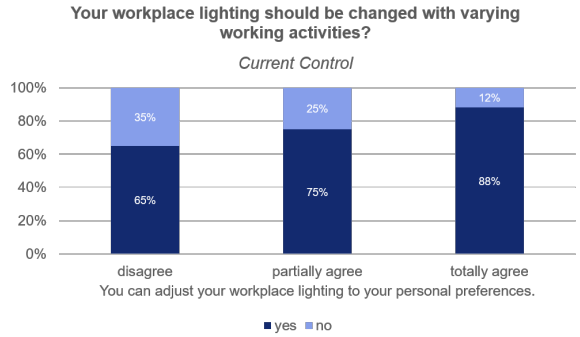

Figure 11: End-users who can already adjust their workplace lighting to their personal preferences overwhelmingly want a lighting that should change with varying working activities.

questions concerning adaptability of illumination and luminaires as well as personalization. While more than a quarter of all people under 30 said that their workplace lighting doesn't need to be improved (compared to 11% for the other age groups), they have other needs than older end-users. For example, while end-users over 40 think it is very important that the brightness of their workplace lighting is increased, users below 30 overwhelmingly want their light colour of their workplace lighting to change.

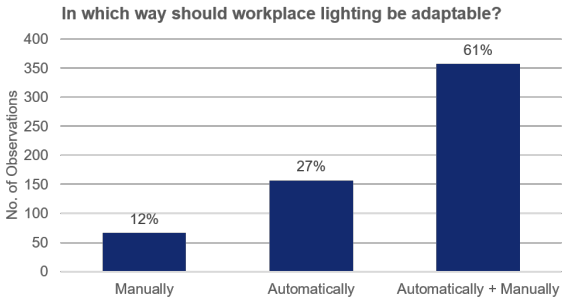

Figure 12: The majority of end-users prefers an automatic control where they have the chance to change the lighting situation also manually.

Concerning the **control strategy** of the light we also see a significant dependence on the age of the end-users. Most end-users want an automatic control where they have the opportunity to change the lighting situation also manually (Figure 12). While only manual control is not particularly popular throughout the age groups, its acceptance becomes wider for age groups above 40. Automatic control (adapts to presence and illumination levels) is most favoured by young people and its acceptance is significantly lower for workers aged 50 or more. In this age group more than two thirds of the end-users want an automatic control of the lighting system where they have the opportunity to change the lighting situation also manually.

At the moment switches and dimmers as well as electronic devices are the preferred **control devices** of the end-users. However, one can see a clear effect with the age of the end-users (Figure 13). For younger people below 30 who have grown up with cell and smart phones electronic devices are mostly preferred, while this decreases significantly when the end-users get older. For end-users older than 40 switches or dimmers are clearly preferred. Interestingly, for the age group 50+ the usage of speech command becomes more favourable again.

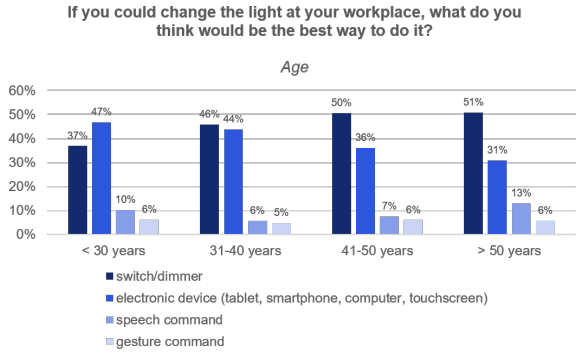

Figure 13: The acceptance of electronic devices for the control of workplace lighting is greatly dependent on the age of the end-users.

Conclusions

The Repro-light consortium wants to develop a luminaire with a modular, stackable architecture that will both reduce time to market by allowing mass customization as well as satisfy the users needs by allowing them to customize and personalize their luminaire. In the first year of the project the focus was on the determination of requirements from a technical and the users' point of view. Results from focus groups and end-user surveys have shown that there is a great need for improvement of workplace lighting in Europe and that the requirements of the end-users are rising in terms of light quality and control.

During the next year the luminaire as well as an automated pilot production line will be developed according to these requirements. In the third project year a large-scale study determining the luminaires impact on office workers will be performed as well as the user acceptance.

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Acknowledgment

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References

[1] E.E.Dikel et al., Lighting-on-Demand: Balancing Occupant Needs and Energy Savings. in LEUKOS, vol. 14(1), 2018, pp. 3–11.

[2] P. Gu et al., Adaptable design: concepts, methods and applications. in Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 223(11), 2009, pp. 1367–1387.

[3] J. Tiihonen et al., An introduction to personalization and mass customization. in Journal of Intelligent Information Systems, vol. 49(1), 2017, pp. 1–7.

[4] C. Huffman et al., Variety for sale: Mass customization or mass confusion?. in Journal of Retailing, vol. 74(4), 1998, pp. 491–513.

[5] Repro-light, D2.2: Requirements Specification, 2018.

[6] Repro-light, D2.1: Stakeholder & Technology Acceptance Report, 2018.

Zhaga: The LpS 2018 Update

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Abstract

In this contribution, we provide an update on Zhaga; covering new specifications, recent market research, the NEW Zhaga, as well as our new collaborations.

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Introduction

Zhaga is an open industry consortium, with some 100 members from the lighting industry, developing interface specifications for components in LED luminaires. The key idea behind Zhaga is as classical as the socket (mechanical interface) to the incandescent light bulb: standardizing sockets, and avoiding proliferation of proprietary form factors, is of great benefit to manufacturers and customers alike. Zhaga has transferred this obvious insight to the LED lighting technology to bring these benefits to LED lighting as well.

Zhaga has been successful in its endeavours and has developed around 15 interface specifications in the course of its existence. In this contribution, we provide an update on our most recent specifications that have been approved during 2017. These are specifications for interfaces of

- LED modules: Book 10 Ed. 1.0 for Spot modules, Book 12 Ed. 1.2 for CoBs and CoB holders, Book 15 Ed. 1.1 for linear modules to be used with lenses in outdoor applications;
- LED modules with integrated LED Light Engines: Book 17 for spot light LED light engines;
- LED modules either with or without integrated LED Light Engines: Book 14 Ed. 1.1 for flat, linear, socketable LED light sources that are suitable for low-profile linear lighting;
- Drivers: Book 13 Ed. 2.0;
- Sensors and connectivity modules: Book 18 Ed. 1.0.

Figure 1 provides a tabular overview of the specifications approved in 2017; in Section 4 we provide a more in-depth description.

Clearly, the key success figure for Zhaga is market penetration of products with interfaces conforming to Zhaga specifications. Zhaga has asked Strategies Unlimited to conduct a market research to probe this important metric. This research has shown that in the top categories (linear, spot and CoB modules) more than 50% of the products shipped by Zhaga members is fully Zhaga compliant. In Section 4, we provide more details.

During the 8 years of Zhaga's existence, the lighting industry has changed. The Zhaga Consortium has reflected on these changes and their impact on its mission and vision. As a consequence, the consortium has recently widened its scope to increase value for its members. Zhaga along with this widened scope is oftentimes referred to as the NEW Zhaga and is properly characterized through its new slogan: "Zhaga: Smart standards. Smarter lighting."

This new Zhaga remains true to its original calling to "specify interfaces of components in LED luminaires". At the same time, the new Zhaga will be better positioned to address new and emerging business propositions in lighting. In a nutshell, the newness in the new Zhaga stems from its ability to better address interfaces for smart components, such as sensors and communication modules, its support of new business propositions from IoT and service economy, as well as its commitment to interoperability.

In Section 4, we update the reader on the new Zhaga.

In Section 4, we cover the main news items in our collaborations with DiiA, IEC, and ANSI, and in Section 4 we conclude.

Specification update

Figure 1 provides a tabular overview of the specifications approved in 2017.

Zhaga has the habit of referring to its specifications as "Books" and linearly numbering them; at the time of writing from 1 up to 18. However, in Figure 1, we have selected another ordering according to component and application area. Thus the electrical components considered in Zhaga are LED module (either integrated with an electrical control gear, or non-integrated), driver, and sensor or communication module. The main application area is currently the professional domain, where we distinguish between Office and industry, Retail and hospitality, and Outdoor; obviously, such a categorization is a first approximation only.

The table show the new specifications that were completed during 2017. Below, we provide a short review of what was new.

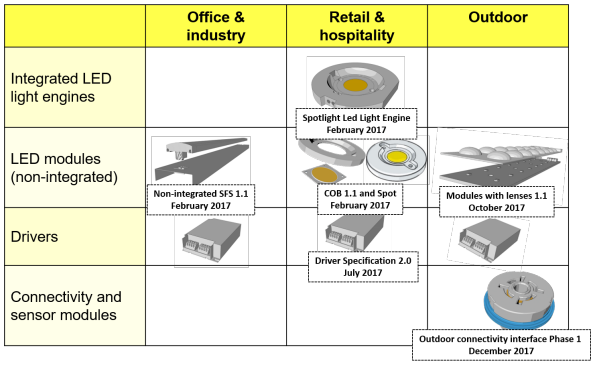

Figure 1: Tabular overview of Zhaga specifications completed in 2017.

Spot modules: Book 10 Ed. 1.0

Zhaga Book 10 defines a family of circular LED modules that have a small circular light-emitting surface (LES). Book 10 LED modules can be used with luminaire optics such as lenses and reflectors, and are typically used in spot-lighting applications.

Book 10 contains simplified and harmonized specifications for the LED modules that were previously described in older Zhaga specifications:

- Book 3 (50-mm diameter LED modules),
- Book 11 (35-mm diameter LED modules).

Book 10 modules can be standalone LED modules, or they can be constructed by combining a COB LED array (defined in Book 12) with an array holder.

CoB and CoB holders: Book 12 Ed. 1.1

Book 12 defines a family of rectangular and square LED arrays with a circular light-emitting surface (LES). These arrays require a separate LED driver, and can be used either with or without holders, depending on the luminaire type and application.

Book 12 Ed. 1.1 extends Ed. 1.0 and also describes array holders.

The outer dimensions of the holder correspond to the LED modules defined in Zhaga Book 10 i.e an outer diameter of either 35 mm (category D35) or 50 mm (category D50).

The combination of a COB module and a suitably-sized COB holder can create a product that effectively replicates a Zhaga-based spot LED module as described in Book 10.

Linear modules with lenses: Book 15 Ed. 1.1

Book 15 defines a family of rectangular LED modules that are intended to be used with lenses or arrays of lenses (also known as lens plates).

The modules require a separate LED driver, and usually will be mounted on a heat sink.

The specification defines several attributes of the LED modules, to enable accurate alignment with the lenses, but the lenses themselves are NOT defined in this specification.

Book 15 modules with lenses are typically used for outdoor lighting applications, including roadway, pathway and outdoor-area lighting.

Book 15 Ed. 1.1 adds a 2×6 form factor, to the three (2×2, 2×4, and 2×8) form factors already available in Book 15 Ed. 1.0.

Spot LED light engines: Book 17 Ed. 1.0

Book 17 defines LED light engines with an integrated driver and a circular light-emitting surface. These are suitable for spot-lighting applications such as compact indoor luminaires.

The maximum LLE diameter is 81 mm, and the maximum height is 15 mm.

The mounting-hole spacing is 35 mm, which is the same as for Book 10 LED modules (category D50).

A range of LES categories is possible, based on the LES diameter, and these are the same as for Book 10.

Due to the integrated driver, these LLEs operate using AC mains voltage

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Flat, linear, socketable LED light sources: Book 14 Ed. 1.1

Book 14 defines a family of flat, linear, socketable LED light sources that are suitable for low-profile linear lighting. Edition 1.1 includes both LED modules (requiring a separate driver) and LED light engines (LLEs) that have integrated control gear.

The LLEs or LED modules have a cap/holder system that enables tool-less replacement. One end of the LED light source has a contact cap, which fits into the corresponding contact holder in the luminaire, while the other end has a support cap and support holder.

The intended application is in free air (i.e., the holders are not surrounded by a luminaire body), or in a luminaire that does not introduce a significant temperature increase.

Drivers: Book 13 Ed. 2.0

Zhaga Book 13 Ed. 2.0 is a significantly updated version of its interface specification 1.0 for LED drivers.

The new specification reduces complexity in the market by having significantly fewer mechanical form-factors than the earlier version. Overall, Edition 2.0 features only 27 categories, compared with 78 in Edition 1.0. This reduction in mechanical form-factor categories represents consensus on a global basis among leading LED driver manufacturers. Removing unnecessary variations in components is a key feature of Zhaga standardization, and is highly beneficial for LED-driver vendors, luminaire makers and customers alike.

Also, Book 13 now addresses the electrical interface between LED drivers and LED modules, which is critical in determining whether components are interoperable.

For the module-driver electrical interface, Zhaga has chosen to reference specifications from MD-SIG, a global industry consortium. Where drivers and modules are compliant with the LEDset Power Interface specification from MD-SIG [1], this allows a meaningful comparison of product data to see if the driver-module combination is a viable option.

Sensor and comuunication modules: Book 18 Ed. 1.0

Book 18 defines a standardized interface between a receptacle on the exterior of the LED luminaire and a sensing and communication module that fits into the receptacle. The standardized interface means that the module can be easily replaced in the field, allowing the luminaire to be upgraded via the addition of new smart capabilities. Also, the luminaire can be shipped with a blank cap in the receptacle, allowing a module to be field-installed at a later date if required. Book 18 Ed. 1.0 defines the mechanical interface between the module or cap and receptacle. However, many non-critical aspects are not restricted by the specification, allowing vendor differentiation and design innovation.

The specification has recommendations for the electrical interface, which features a 4-pin connector. The recommended pin assignment enables the required 24 V DC power supply, as well as DALI control and a general Logic Signal Input (LSI).

Book 18 Ed. 1.0 offers a number of advantages compared with the existing ANSI/NEMA standard C136.10-2010. This describes locking-type photo-control devices and mating receptacles and is used mainly in the USA and the UK. Book 18 Ed. 1.0 enables modules with a much smaller footprint, which in turn will allow greater design flexibility for the luminaire. Also, the Zhaga specification uses 24 V rather than mains voltage.

As another key advantage, the Zhaga Book 18 interface allows the module to be mounted underneath the luminaire, facing downward. This enables key applications such as motion detection and security cameras.

Figure 2: The Zhaga Book 18 connectivity interface allows the module to be mounted underneath the luminaire, facing downward, enabling new key applications such as motion detection and security cameras.

Market research

At the end of 2017, Zhaga asked Strategies Unlimited to conduct market research into Zhaga. A first research focused on the prevalance of Zhaga compliant LED modules. In a second research, the readership of LEDs magazine and LUX Review was approached with more general questions about Zhaga and standardization.

Market penetration of Zhaga compliant LED modules

The focus of this research was to determine the market penetration of specific LED module form factors that are compliant with the organization's standards. For this, a selected set of relevant manufacturers was approached.

Core questions asked were

- To what extent are your Linear LED Modules for Indoor Lighting compliant with Zhaga specifications?
- To what extent are your COB Arrays compliant with Zhaga specifications?
- To what extent are your Holders for COB Arrays compliant with Zhaga specifications?
- To what extent are your Circular LED Modules for Spotlighting compliant with Zhaga specifications?

The respondents were provided a range of answer categories ranging from "certified" to "not at all compliant". Additionally, respondents were asked after the number of units shipments of these module categories.

The set of actual respondents to the survey was biased towards the Zhaga members (with also former members replying) so that no general conclusions could be drawn about the percentage of Zhaga compliant modules in the market. However, the representation of Zhaga members was sufficient to make statements on this population.

The results for the linear modules are presented in Figure 3. It shows the weighted average compliance of Linear LED Modules for Indoor Lighting. In the graph, fully compliant means either "certified" or "fully compliant but not certified". The figure shows that about 50% of the linear modules shipped by the companies in the survey were fully Zhaga compliant.

The results to the other questions were rather similar; for spot modules the percentage of compliance was even higher, whereas for CoB modules it was a bit lower.

In all, the results show that the Zhaga standardization works, and support the claim that "Zhaga members declare: In the top categories (linear, spot and COB modules), more than 50% of products shipped were Zhaga-compliant"

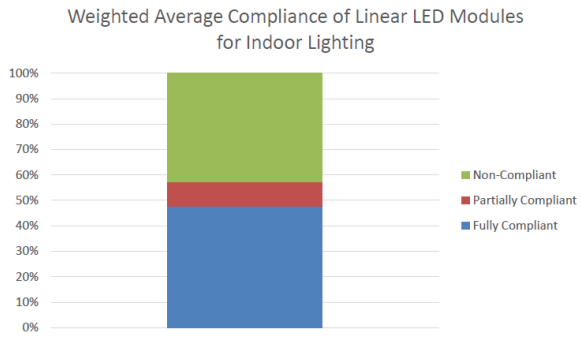

Figure 3: Estimated percentage of compliant linear modules in portfolio of Zhaga members.

General questions on Zhaga

In a second research, the readership of LEDs Magazine and Lux Review was approached with more general questions about Zhaga and standardization. The survey yielded a good response, with approximately 500 respondents, equally distributed over "Manufacturers of LED products", "End users", and "Others".

Of the replies given, one stood out, see Figure 4: to the question "Do you think there should be standards for connected lighting products?", an overwhelming majority of 97% answered "Yes". In general terms, we may conclude from this answer that standards setting organizations have an important role to play in making a success out of connected lighting. The Zhaga contribution to connected lighting is through "connectivity interfaces" as we will detail in Section 4.

The NEW Zhaga

The Zhaga task force "Strategy", led by Giovanni Scilla, Chair of the Steering Committee, has investigated opportunities for Zhaga offered by recent trends in the lighting industry. Particularly relevant are here the combination of LED lighting and lighting digitalization, the need of light designers and architects for components that can

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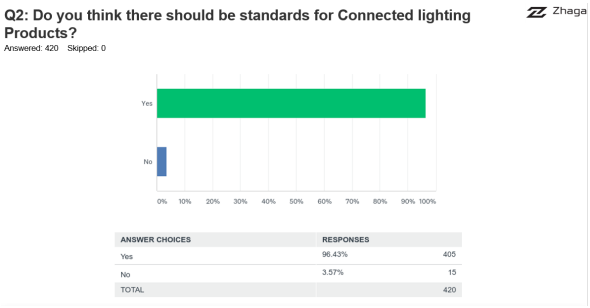

Figure 4: Do you think there should be standards for connected lighting products?

be assembled easily, also at a late stage, by means of standardized interfaces, as well as requirements put on lighting systems from a circular economy perspective. This has led to what was termed the NEW Zhaga, and a new Consortium Agreement, with a new Scope and IPR policy.

Benchmarking against the “current Zhaga”, there is a lot of continuity: the new Zhaga remains true to its original calling to “specify interfaces of components in LED luminaires”. Also, it will keep the specifications as thin as possible to maintain design freedom and scope for differentiation.

At the same time, the new Zhaga will be better positioned to address growth areas in lighting. In a nutshell, the newness in the new Zhaga stems from its ability to better address interfaces for smart components, such as sensors and communication modules, its support of emerging business propositions from IoT and service economy, as well as its commitment to interoperability.

Below we present the new vision and mission of the new Zhaga; therefater, we zoom in on same key aspects of the new Zhaga: Interoperability, connectivity interfaces, serviceable luminaires, and a new membership class called Community Membership.

Vision

The Vision of the Zhaga Consortium is:

- On top of their primary lighting task, LED luminaires are becoming increasingly smart and connected to IoT networks.
- The design of a new luminaire is facilitated by the availability of a large supply of interoperable components, based on standardized interfaces, while still encouraging differentiation.
- Zhaga creates specifications for electrical, mechanical, optical, thermal and communication interfaces for interoperable components to be used in LED luminaires.
- These interoperable components allow the upgrading and servicing of LED luminaires, depending on the design choices by the luminaire manufacturer.
- The ability to upgrade LED luminaires after installation is of great benefit to end customers. Their luminaires are future proofed to embrace upcoming innovations in the lighting industry, including the digital innovations beyond lighting.
- The ability to service LED luminaires encourages more resource efficient business models that meet circularity requirements, including legislation and drive market growth.
- The Zhaga logo proves the certification of interoperable components and provide an easy means to identify components that can be upgraded and serviced.

Zhaga creates new opportunities for the lighting value chain in the innovations beyond lighting.

Mission

The mission of the Zhaga is

- To create specifications for electrical, mechanical, optical, thermal and communication interfaces for interoperable components to be used in LED luminaires, or fixtures.
- To make components easily identifiable, and third party tested, through a logo licensing program.
- To enable manufacturers to make LED luminaires with Zhaga-compliant components, which are upgradeable and serviceable, depending on the design choices taken by the luminaire manufacturer and the serviceability level of the luminaire.
- To promote the benefits and opportunities of using Zhaga-compliant components for new luminaire use cases to manufacturers, specifiers, installers and professional end users.
- To actively share Zhaga specifications with other global and regional standards development organizations, as well as

national lighting organizations, gaining increased global acceptance of the Zhaga specs.
- To maintain design freedom and scope for differentiation, by only restricting those parameters necessary to enable interoperability.

Interoperability

The new vision and mission mention interoperability multiple times as a key concept for the new Zhaga. The Zhaga use of this concept is fully consistent with common usage, as, e.g., in the Cambridge dictionary: if two products, programs, etc. are interoperable, they can be used together. Yet, the concept is subtle, as the "can" in the definition has an implicit reference to a user competence. Firstly, it refers to an element of information and requires an ability of a user to verify that products can work together and that there are no incompatibilities. Secondly, it refers to an element of operation and requires ability of a user to actually make things work together.

Some examples are in order:

- An engineer at an OEM may decide that components are interoperable if he is able to verify that there are no incompatibilities (e.g., thermal through simulations) and if they can be made to function together using the tools at his avail (e.g., after selecting appropriate cables, connectors, etc.)
- An installer may decide that components are interoperable if he is able to verify that there are no incompatibilities (e.g., thermal via a label, electrical via arithmetic comparisons) and if they can be made to function together using the tools at his avail (e.g., ability to open the luminaire, insulated screw driver, . . .)
- An end-user may decide that components are interoperable if he is able to verify that there are no incompatibilities (e.g., a label) and if they can be made to function together without tools. Often, an end-user may trust that products are interoperable if they fit: plug and play.

As of current Zhaga has focused on specifications that enables an engineer at the OEM to judge interoperability; another set of specifications was developed for end-user typically through LED light engines integrating both modules and drivers. In the new vision use cases, such as late stage configuration or upgrade in the field, that will typically involve installers and luminaire architectures with separate modules and drivers. This will require a more sophisticated elaboration of interoperability.

The pursue its vision of interoperability, the NEW Zhaga has a number of tools to its avail:

- Interface restrictions — to ease verification
- The use of connectors and fit systems to ease installation
- Consideration of all aspects of the interface.

Connectivity interfaces

A connectivity interface interfaces the luminaire and its driver electronics to a sensor or communication module. This interface makes it easy to upgrade LED fixtures by mounting or changing modules that provide sensing and communication capabilities. The interface allows for a separation of concerns between the lighting and IT, and future proofs fixtures in view of the rapid changes in the IT industry such as the fast succession of next generations of connectivity technology. It also provides great efficiencies for luminaire manufacturers, as one luminaire may be configured at a late stage with one of the many different and competing connectivity and sensing technologies.

To be economically viable, it is essential that this interface is developed as a standard. A large installed base of luminaires with this interface will drive a large ecosystem of sensors and connectivity modules, which will in turn add value for the luminaires and drive growth of the installed base of luminaires. It is not feasible to get these reinforcing forces going in a fragmented industry with proprietary interfaces.

Zhaga has connectivity interfaces as a core standardization topic, and is well on its way to realizing the vision for outdoor luminaires, securing a central place for lighting in the smart city. Its very well received Book 18 Ed. 1.0 describes a mechanical interface; see Figure 5 for a picture. At the time of writing, Zhaga is planning on the control and power aspects of the interface, to be developed in the new Zhaga joint with the Digital Illumination Interface Alliance (DiiA), so as to arrive at a true plug-and-play interoperable solution. As a next step, the new Zhaga will

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develop a connectivity interface for indoor, with similar plug-and-play properties.

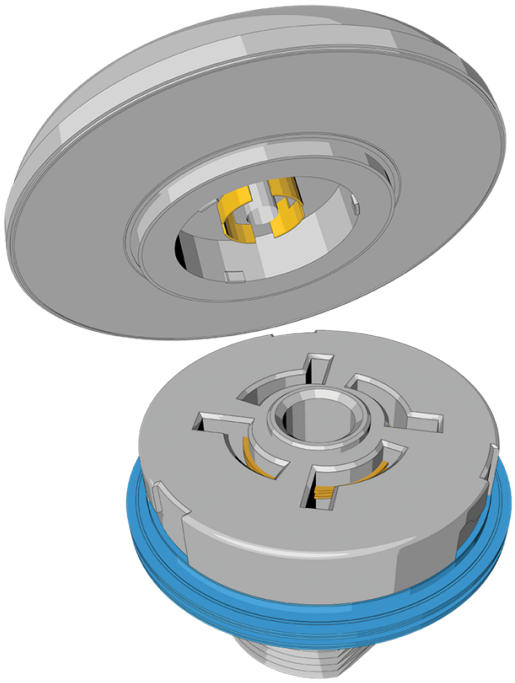

Figure 5: Zhaga Book 18 describes the mechanical aspects of a connectivity interface for outdoor luminaires; it will be complemented with control and power aspects of the interface, to be developed in the new Zhaga joint with the DiiA, so as to arrive at a true plug-and-play interoperable solution.

Serviceable luminaires

The ability to change or reconfigure parts of an LED system — such as a module or a driver — to accommodate changes in performance, appearance, taste, functionality, building layout or utilization, or latest technology advancements is of great benefit to end customers. There are many business drivers for this ability, such as repair, upgrade, innovation to market, late stage configuration, SKU management, circular economy possibly in combination with regulation. Already well-established business opportunities can be found in outdoor and horticulture.

Zhaga has ample experience with serviceable luminaires through its specifications of interfaces for LED light engines, e.g., modules with integrated control gear; see, e.g., Figure 6. However, at current it seems that the architecture with module and separate control gear is favoured in the market. To also support serviceability for this luminaire architecture is still a considerable challenge.

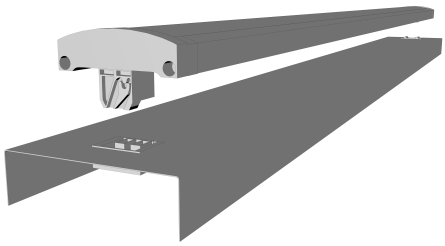

Figure 6: Zhaga Book 14 describes a family of flat, linear socketable light sources with great plug and play features.

At current, two things are clear. Firstly, that well-defined component interfaces are essential to develop the business propositions. Secondly, that the new Zhaga Consortium is fully prepared and set up to come up with creative solutions to meet the challenges. The developed eco-system for spot modules, comprising COBs, holders, coolers, and optics, though not developed as a fully serviceable proposition, at least indicates the direction to go. More examples are developing within Zhaga.

Community Membership

The new Zhaga will develop a membership class called “Community Membership”. Community membership is arranged via a formal contract, but at zero fee. Targeted member companies are specifiers, installers and professional end users. Through this membership class, Zhaga will be better able to share information with a class of companies that do not manufacture (Zhaga) products, and to get feedback on proposed specifications and application requirements.

Teaming up

The scope of the new Zhaga is widened to all aspects of all interfaces of components is LED luminaires. This puts the consortium in an excellent position to become THE interface organization for smart luminaires. At the same time, the consortium does not operate in a vacuum, but rather in an environment with many other organizations that develop standards relevant for LED lighting. The new Zhaga will follow up on the path set already set out and keep an open eye on external developments and will not develop itself specification that may be available (or are better developed) elsewhere.

Our collaboration with DiiA, ANSI and IEC serve as proof points for such teaming up. With DiiA, a liaison has been established and a collaboration over DALI-based communication interfaces. These communication interfaces complement the work done in Zhaga on connecivity interfaces, see 4. Close collaboration between the two organizations is essential to guarantee full plug-and-play interoperability between luminaires and communication/sensor modules, as described in Section 5. Close collaboration is also essential to guarantee a smooth testing and certification flow that is both practical and feasible for members of both organizations.

The organizations expect to make concrete statements about their collaboration at the LpS 2018 conference.

ANSI C136 and Zhaga signed a Memorandum of Understanding to provide ANSI C136.54 with early access to Book 18, and so enabled the consideration of the Book 18 interface in this working group.

IEC has recently published Zhaga Book 7 “Linear modules” as a Publicly Available specification (see [2]). Within IEC, TC34 AG13 is overviewing the next step targeting a full integration of the Zhaga specification into the IEC standards. We see this as the right operational model moving forward. Zhaga will target fast development cycles, and has the right mix of companies mix to allow for fast products to the market. The IEC then is the right environment for further harmonization with existing standards, building broader support, as well as maintenance for the specifications that ae mature and have proven themselves successful in the market.

Conclusions

In this paper, we have presented the reader an update on Zhaga, and reviewed what has happened in the course of 2017. We hope that at least a picture of an active and engaged community has emerged, eager to serve the lighting community with winning standards. Zhaga standards have been successful in simplifying existing markets, by reducing the amount of arbitrary variation that does not yield value for the customer. Clear examples with high market penetration are the form factors for LED modules.

With the widened scoping, and new vision and mission, Zhaga is better positioned to address growth areas in lighting. With its focus on serviceability and connectability, it will develop specifications that open up new markets. The outdoor connectivity interface, as well as the upcoming indoor interface, are concrete proof points already of the value of new Zhaga. Specifications are in the making to also implement our vision for other components in the luminaire.

We believe that companies from the full value chain will benefit from these new markets. We also believe that a standards-setting organization is only as relevant as its support in the industry. Zhaga was and remains an open industry consortium and invites all companies from the lighting value chain to join and to jointly live the vision and mission in pursuit of value for the whole of the lighting industry.

References

[1] MD-SIG, The Module-Driver Interface Special Interest Group, www.md-sig.org.

[2] Zhaga interface specification Book 1 and Book 7, IEC/PAS 63166:2018.

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Lighting Goes Smart — Should We Care About Cybersecurity?

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Abstract

Innovation is the cornerstone of modern technology. Innovation enables creation of new products and solutions that can bring growth and increased productivity to an industry or market and that delights the consumer. One of the newer innovation technologies transforming the way we do business, manufacture and build products and services and how we interact personally and professionally is the connected space.

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Figure 1: Lighting Systems and Cybersecurity.

Lighting Systems and Cybersecurity

Connected products and systems allow for the easy ability to interoperate devices, control disparate systems and function in an ever increasing connected world. However, increasing the extent of connectivity comes with the risk of less safety and security unless those invested in providing a connected world and all of us, as stakeholders, take appropriate steps to help ensure necessary safety and security measures are implemented and maintained.

Cybersecurity provides a new holistic challenge to overcome a more connected world.

Infrastructure is increasingly relying on smart, automated control systems with devices or sensors that communicate with each other via embedded communications technology. These communications enable a facility, traffic lighting and control system, an industrial manufacturing or power plant or a high rise office or residential building to perform their required functions and to respond to detected changing conditions. While advanced technology has overcome the technical hurdles of distance, environment, bandwidth and reliability, there is an evolving need to address intrusion into the orderly communications within the infrastructure systems. Making sure the cybersecurity posture of the individually connected equipment is relevant, safe and secure allows for these connected systems to perform as their designers, installers and operators intend.

The global media is awash with reports of information hacking attempts, the serious consequences of the “discovered and publicized” ones, and the vulnerability we all face in an increasingly connected world. Both the public and private sectors are concerned about this threat and are looking for ways to reduce how vulnerable they can be to possible intrusion or hacking. The lighting industry is not immune to cybersecurity threats and can be increasingly vulnerable as lighting systems technology embraces the opportunities presented by interconnection, especially that offered by the Internet of Things. Cybersecurity threats take many forms and they therefore must be addressed at the hardware, software, system and operational / procedural levels. The extent to which measures need to be taken and how sophisticated (and expensive) those security measures need to be will, of course, depend upon the potential risk associated with a successful cyber-attack. For instance, the neighbor teenager who switches your living room lights on and off is a nuisance, a low level threat. On the other hand, turning off all the lights at a critical infrastructure location (e.g., power plant) may have severe consequences, especially if it is accompanied by additional attacks, cyber or otherwise.

Figure 2: Lighting systems will increasingly be integral parts of other systems. They will directly or indirectly (serving as sensors) be relied upon by building automation, energy management, data transmission, public safety, security and location systems and services. This will result in cybersecurity expectations being placed on lighting systems by the purveyors of these complementary systems as well as those responsible for maintaining them.

This paper will examine the following:

- Overview of basic cybersecurity threats
- IEC & U.S. standards currently addressing cybersecurity
- Efforts to address cybersecurity in lighting standards

What are Cybersecurity Threats

Figure 3: The occurrence of a cybersecurity incident is predicated by the current state of three variables: Vulnerability, Threat Actor, and Opportunity.

Vulnerability

Vulnerability is the term that describes flaw(s) in a product or system that allows an individual (threat actor) to circumvent any security measures to gain unauthorized access or cause the system to operate in an unintended way. For example: a device that has a factory installed password that was not modified after installation.

Most vulnerabilities fall into one of four types:

- Design vulnerabilities: a security flaw in the design of the product or service.
- Implementation / configuration vulnerabilities: misconfiguration of a product or service design capabilities (e.g., the above example of failure to update a password).
- Communications vulnerabilities: unsecure content (e.g., lack of encryption) or susceptibility to manipulation.

Threat Actor

An individual who can take advantage of a vulnerability in a product or system is known as a threat actor. They can be nation states, organized or individual criminals, hobbyists and hactivists and an insider or employee.

Opportunity

Opportunity describes the product, system or data to be accessed, altered or denied. A neighbor's lighting system is an opportunity for someone determined to be a nuisance by adjusting the neighbor's lighting settings. Or a criminal gang may identify a city's street lighting system as an opportunity that enables access to the city's other systems.

Typically, the risk of a cybersecurity incident increases when a vulnerability exists in a product or system, a threat actor wants to access the infrastructure and there exists some reason or opportunity that would provide the threat actor with a motive. As the sophistication of the threat actor increases with the commercial availability of hacking tools, and the motive to perform a cybersecurity hack exponentially grows because of the connected infrastructure, we need to determine how we can increase a security posture to manage the risk by taking actions to prevent or mitigate an intrusion.

When you take a look at some of the types of vulnerabilities that exist in products in most domains, they have a few common attributes. Wireless communication comes in many forms with varying degrees of sophistication. Encryption techniques are surprisingly not always as robust as they can and ought to be. In software embedded in devices, some of the common vulnerability attributes are remote control protocols, unsecure web services, buffer overflows, weak authentication mechanisms and SQL errors common on data loggers. They have become so common that CWE/SANS has developed a Top 25 list of software weaknesses that cause significant security holes in products and systems.

IEC and U.S. Standards

The standards and technical specifications are organized into four categories:

- Policies and procedures cover an "asset owner" or the person responsible for a deployed infrastructure with industrial automation and control system security.
- System — provides criteria to support and develop installing, deploying and servicing an infrastructure with industrial automation and control system security.
- Component — provides criteria to product vendors in developing, building and manufacturing more secure products.

These standards have developed quite a following

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Figure 4: International Electrotechnical Commission (IEC) and U.S. standard bodies have been developing standards that address cybersecurity concerns of equipment and systems and typically support a particular industry or functional ecosystem. One of the most significant international efforts currently underway is the IEC 62443 series of standards prepared by the IEC technical committee 65 — industrial process measurement and automation. This is a series of standards and technical specifications published under the general title industrial communication networks — Network and system security.

outside of their intended industrial application. They offer one of the most comprehensive approaches to requirements addressing major areas of cybersecurity proficiency, much of which is broadly applicable to most industries, including lighting, and not just industrial.

Leveraging the IEC 62443 standards as a reference, the IEC Advisory Committee on Safety (ACOS) is currently developing guidance for IEC standards writing committees using the framework of those standards on safety-related security. Safety-related security is currently proposed to be addressed and classified in one of the following categories:

a) Protection against casual or coincidental violation,
b) Protection against intentional violation using simple means with low resources, generic skills and low motivation;
c) Protection against intentional violation using sophisticated means with moderate resources, specific skills related to the considered equipment and moderate motivation; and,
d) Protection against intentional violation using sophisticated means with extended resources, specific skills related to the considered equipment and high motivation.

The IEC 62443 standards start with how a vendor designs and builds a product or system taking into account the intended functional security required and specified for the product. They address the common software weaknesses that can enter a product, poor coding practices and known industrial control equipment security flaws that should be addressed before a product is shipped. A mechanism is identified to initially evaluate and audit on an ongoing basis that a vendor is producing secure products by using industry practices for a secure development life cycle, proper hiring and policy practices and good “cyber hygiene” in the facilities and infrastructure used in the design and development of the product. Finally, the standards address the operator’s installation, deployment and maintenance of an industrial control system and interaction with an IT system.

The U.S. has also been developing mechanisms to assess how an organization has protected itself from possible cyber intrusions and recovery mechanisms. With the advent of the Smart Grid in 2009, the U.S. National Institute of Standards and Technology (NIST) formed an entity called the Smart Grid Interoperability Panel (SGIP) to develop interoperability and cybersecurity standards for the connected devices and systems in a smart grid environment. Forming a cybersecurity working group out of participating utilities, vendors, academic institutions and consulting organizations, they developed a NIST Interagency Report 7628 guidelines for Smart Grid Cybersecurity. This guideline was developed with the intent to assist and support electric utility operators on how to strengthen their cybersecurity posture.

NIST also released in 2014 a Cybersecurity framework for improving critical infrastructure. The framework involved a collection of maturity model criteria to address cybersecurity pointing to several different cybersecurity standards or guidelines. This framework has significant international appeal because of its overall intent in helping a critical infrastructure operator in defining and developing mechanisms to identify its cybersecurity risk profile and introduce capabilities to manage the risk.

Efforts to Address Cybersecurity in Lighting Standards

Most industries have been looking at ways to address cybersecurity. Some industries have focused on working on standards and guidelines to help a vendor build better products. These typically would involve an organizational or process type audit. Other industries have looked at developing prescriptive technical requirements for products to augment existing performance or safety standards. In lighting, the cybersecurity emphasis depends on the type of product ecosystem.

Consumer lighting products and systems typically installed are often integrated with home or building energy management system that is also integrated with an HVAC system. Standards can potentially address basic cybersecurity protective measures that products today may lack or where protective measures have become out-of-date. Assessing the risk associated with cybersecurity vulnerability in these products will identify the measures that are economically feasible to implement.

Figure 5: Industrial and critical infrastructure lighting, for example, that is used in street light and traffic control systems, needs more robust protection measures. The risk to the public, the institutions and utilities that the public depends upon is much more significant for these applications. The standards must address sophisticated means of intrusion, potentially from threat actors with significant resources. Clearly, a one-size-fits-all solution is not practical or advisable for the lighting industry. An overall strategy on resolving inherent security vulnerabilities in products is needed.

Below, we will consider some examples of security measures that the lighting industry should consider to strengthen the security posture of these systems.

Proper Technology Prescriptive Criteria

There should be a development of specifications on how products are designed to help ensure security vulnerabilities are addressed. Criteria will include the use of cryptography for secure communications and storage of information. Encryption for devices that communicate is important; encryption that is confirmed to be difficult to circumvent reduces the risk that lighting systems and components are viewed as an opportunity. Use of encryption with the correct key sizes help make a product secure.

Some encryption algorithms allow for different key sizes but attention should be made for the key sizes that are inherently weak for the current computing power that exists today. For example, Triple DES is a popular well known encryption mechanism. However, a vulnerability is its ability to have weak key sizes. These should be identified and not allowed in product specifications and industry standards unless the use is allowed where the cyber risk is otherwise negated.

Factory defaults should be considered and forcing a user to change them or having an indicator that they still exist in the product should be standard practice.

Use of open source technologies that have known vulnerabilities is a major source of cybersecurity incidents in industrial facilities and there is no reason to believe this isn't more universally the case. Having a known vulnerability in a product that is shipping allows a potential threat actor an easy access into the lighting device and then the system it is connected to. For instance, use of a SSL library that has published known vulnerabilities provides the threat actor with a published way of circumventing the product's security measures.

Secure Development Life Cycle

Designing and building products using a process that takes security into account is another major factor in addressing cybersecurity in lighting products. A vendor's cybersecurity training investment for software and hardware developers can address many vulnerabilities at the source, before it leaves the design phase and when it is least expensive to implement.

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Using a method called threat modeling, a process to identify possible security flaws in the design of a product, assessing the risk associated with the flaw, and correcting the flaws or inserting mitigation criteria to reduce the risk helps a product become more secure. There are several models that exist today. Most models set up a methodology for addressing security concerns in developing product software that starts from the requirements gathering phase to an incident response phase. The models enable identification of vulnerabilities that may exist in a product design and produces a vulnerability threat analysis so the vendor can mitigate them during the less expensive design phase.

One of the most important attributes of a secure development life cycle is tracking of new vulnerabilities that may be found once a product is released. Once these vulnerabilities are found, addressed and applied to newer software versions, a vulnerability and patch management process for the vendor aids in communicating with users. New software, a source for new verified software and its location, and a check mechanism that unverified software cannot be installed on a product can be deployed.

Figure 6

Organizational and Process Evaluations

Excellent quality metrics already exist for the product development and manufacturing process; they are used to assess a vendor's ability to provide adequate quality assurance on the products they produce. Six Sigma and Capability Maturity Models are tools employed by larger organizations to validate and verify that they are using statistically sound quality management processes. This has been expanded on when adapted for the cybersecurity domain and represents a best practice for all enterprises, large and small.

New models of assessing a vendor for developing secure products can also add significant value. Some of these models follow hiring practices, training and stage gate mechanisms for design engineers, proper configuration management techniques and secure development techniques. Making sure there is security around the source code repository, how it is built and tested, who can access it, and when they do, an audit log of what was done is imperative to ensuring a vendor is a "secure" builder of products.

Conclusion

In today's connected world, as we create, sell and use more products that communicate and are interoperable with each other, any product can be an opportunity and serve as a gateway into an otherwise protected organization. That product can either be a weak link or robust barrier to unauthorized access so that a threat actor moves on to something else. Developing industry agreed upon technical criteria provides a level playing field for competing products.

Figure 7

Assessing and auditing a vendor's process of designing and producing products, combined with strong technical standards, tells the marketplace what the lighting industry considers acceptable cybersecurity practices. This can only raise a buyer's confidence that the supply chain for lighting products takes cybersecurity seriously and is a partner with the producers of other connected systems in assuring cybersecurity performance that meets best practices. Otherwise a connected world is not secure and the use of connected systems would be significantly

constrained and the enormous benefits not realized.

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Metameric Circadian Lighting: A Technology Analysis

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Abstract

This paper analyses how metameric lighting solution can effect circadian effects. Different spectral power distributions (SPDs) are generated by combining LED spectra of 5 colors. The combinations have the same white tone but differ in their composition of the spectra. They are characterized by non-visual as well as visual parameters. The analysis compares lighting solutions for the standard office lighting requirement to have a CCT of 4000 K. A difference of the circadian stimulus (CS) above 0.2 with a constant irradiance of 0.5 W m^{-2} can be achieved. It is only possible in the expense of color rendering properties. Keeping a CRI above 80, the generated SPD result in a CS better than 0.05. A combination of spectral and spatial distribution of light is suggested.

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Introduction

Nowadays most people spend the majority their day inside, where they are exposed to artificial lighting. The absence of natural light can cause health problems in humans as a disruption of the circadian rhythm, depression and sleep quality [1][2][3]. The discovery of the non-visual photoreceptors, the so called intrinsically photosensitive retinal ganglion cells (ipRGCs) [4] started research developments and effort for lighting solutions to promote human health (broadly known as Human Centric Lighting, HCL).

Light is the most important *Zeitgeber* for circadian rhythms of our inner clock according to chronobiology experts [5]. The light detected by the ipRGCs cause secretion and suppression of melatonin [6][7], which affects our circadian physiology [1], alertness [8] and cognitive performance [9]. Research focus to resemble daylight spectral power distributions (SPDs), and adjusting the blue part of the spectrum [10] and therefore changing also the correlated color temperature (CCT) of the light.

Not only non-visual but also visual parameters have to be taken into account in order to develop lighting solutions which are accepted and implemented. The requirements differ depending on the application (e.g., office, retail, home). For retail stores an excellent color rendering is crucial and for many indoor applications and on locus white tone is preferred.

The sensitivity of the visual photoreceptors (rods and cones) and non-visual photoreceptors (ipRGCs) are shifted in their spectrum. Thus different circadian effects can be produced by the same visual stimuli and make therefore the concept of metameric light sources promising. Metamers are optical stimuli that are spectrally different but chromatically equivalent. The idea is to trigger different non-visual effects by changing the spectral distribution but keeping the CCT constant.

The parameters that characterize the quality of a light source are chromaticity coordinates (CIE x, CIE y), color rendering index (CRI), correlated color temperature (CCT) and luminous efficacy of radiation (LER). We characterize the non-visual effect of the light with the circadian stimulus (CS), suggested by Rea *et al* [11]. LEDs are very well tunable and are available in a wide range of colors. They are thus well-suited for combinations to receive different SPDs. A large number of current approaches change CCT. For some applications one wants to maintain a constant white tone though, for example to keep the appearance of illuminated objects the same. We aim for the standard of office lighting, a CCT of 4000 K. To maximize and minimize for non-visual effects we use the model proposed Rea *et al*.

Characterization of SPDs

To characterize the visual and non-visual performance of LED combinations the sensitivities of the different photoreceptors in the human eye are necessary.

The photopic sensitivity V(λ) ([15]) describes vision at well-lit conditions and the scotopic sensitivity V′(λ) ([15]) at low light levels. For non-visual effects the sensitivity of the melanopsin containing ipRGCs is crucial, which have a blue shifted peak (see Figure 1).

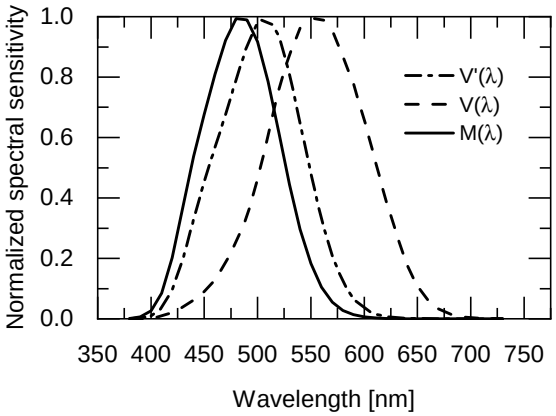

Figure 1: Normalized spectrum of the photopic sensitivity curve V(λ) of a 10° observer, the scotopic sensitivity curve V′(λ) and the melanopsin-containing retinal ganglion cell spectral efficiency function M(λ) maximum peak at 484.0 nm [12].

An overview of the key parameters for visual and non-visual performance is shown in Table 1.

The CCT is calculated with the formula suggested by Ohno *et al.* [17]. The luminous efficacy of radiation is defined as:

$$\mathrm{LER} = 683(\mathrm{lm/W})\frac{\int \mathrm{V}(\lambda)\mathrm{E}(\lambda)\mathrm{d}\lambda}{\int \mathrm{E}(\lambda)\mathrm{d}\lambda} \qquad (1)$$

where V(λ) is the visual sensitivity curve and E(λ) the spectral power distribution of the light source.

There are different methods suggested to evaluate the effect on the circadian rhythm, the

Table 1: Visual and Non-visual parameters for characterization of metameric lighting.

Quantity	Abbrev.	Unit
Vision performance		
Color coordinates	CIE x,y	1
Correlated color temperature	CCT	K
Luminous efficacy of radiation	LER	lm/W
Color rendering index	CRI	1
Non-visual performance		
Circadian stimulus CS	CS	1
Circadian action factor	CAF	1

internal sleep-wake cycle of humans. Rea *et al.* developed a circadian response function, the circadian stimulus (CS) ([11][12]) which describes the suppression of the hormone melatonin by one hour retinal illumination. CS is a function of circadian light (CL_A) (see Figure 2). It is within in a range of 0 and 0.7, where 0 corresponds to a melatonin suppression of 0% and 0.7 to the maximum of 70 %. An advantage of the model is that it takes into account the fact that rods and cones participate to the circadian effect. It includes relevant biological mechanisms such as blue-yellow opponency and rod saturation. A point of criticism is that the circadian efficiency function they suggest is a step function, instead of a continuous function. For a detailed description of the formula see [12].

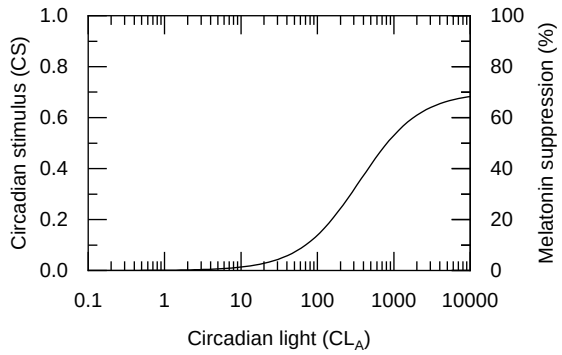

Figure 2: The relative melatonin suppression as a function of circadian light (CL_A). It is scaled for a 2856 K blackbody radiation at 1000 lux having a value of 1000.

Other groups as Gall *et al.* [13] developed their own spectral weighted circadian sensitivity curve $C(\lambda)$, based on the experimental data of Brainard *et al.* [6] and Thapan *et al.* [7]. Another method for characterization of circadian effect is the circadian action factor (CAF). It is defined as

$$CAF = \frac{\int C(\lambda)E(\lambda)d\lambda}{\int V(\lambda)E(\lambda)d\lambda} \quad (2)$$

It is a measure for the ratio between visual and non-visual performance of a light source. It is broadly used to characterize non-visual effects of light sources. Therefore the CAF with $C(\lambda)$ proposed by Gall *et al.* [14], is calculated complementary to the CS for the generated SPDs.

Within experts there is no agreement yet for a common figure of merit.

Recent work in the context of circadian effects of light sources considering relative participation of different photoreceptors is done by Lucas *et al.* [18] and Amundadottir *et al.* [19].

Results and discussion

Metameric SPDs are generated and optimized for their effect on circadian rhythm. They are analyzed with the parameters for visual and non-visual performance. The SPDs are a combination of 5 colored LEDs. We use the spectra provided by OSRAM Color Calculator ([16]) with the following peak wavelengths: λ_1 = 624 nm (red), λ_2 = 594 nm (yellow), λ_3 = 530 nm (green), λ_4 = 505 nm (verde) and λ_5 = 455 nm (blue). In order to have photometric comparable solutions, the solutions all have a constant irradiance of 0.5 W m^{-2}. In order to have a maximal and minimal effect of a lighting solution of 4000 K on the circadian rhythm the SPD are optimized for their CS. To limit the noticeable difference of the white tone we apply the ANSI C78.377A standard, which is of widespread use in lighting. For a 4000 K light source the limit for the CCT range is 3985 K $\pm$ 275 and a Duv $<$ 0.006. Figure 3 shows the SPDs of four different conditions. SPD 1 and 2 have the maximal and minimal possible CS but no restriction on the CRI. SPD 3 and 4 a restriction of a CRI above 80 is implemented. Table 2 shows the visual and non-visual parameters of the calculated combinations.

Comparing SPD 1 and 2, they have a difference in their CS of 0.24. Thus remarkably we can generate two 4000 K spectra which will have a variation 25% in melatonin suppression. Their difference in CAF is below 0.1, which is comparable low. This might result from the different circadian sensitivity spectra used for the

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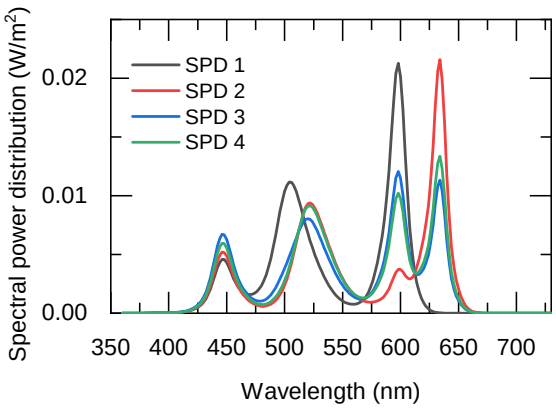

Figure 3: Metamer LED combinations. The spectra are optimized for CS. The SPD are generated as a combination of 5 LEDs of the colors: red, yellow, green, verde, blue. They resemble typical office lighting standard where a color temperature of 4000.0 K is desired. SPD 1 is has a minimized CS, SPD 2 has a maximal CS, SPD 3 a min. CS as well as a CRI above 80, SPD 4 max. CS and CRI above 80.

Table 2: Analyzed parameters of 5 channel LED combinations.

	SPD 1	SPD 2	SPD 3	SPD 4
CRI x	0.384	0.385	0.378	0.381
CRI y	0.390	0.391	0.367	0.389
CCT	3995	3978	4013	4054
CRI	58.4	47.8	80.9	81.0
Duv	0.0051	0.0052	0.0039	0.0054
Δu'v'	0.0068	0.0070	0.0051	0.0072
LER	358	304	327	336
CAF	0.543	0.495	0.547	0.492
CLA	637	170	249	194
CS	0.459	0.215	0.282	0.238

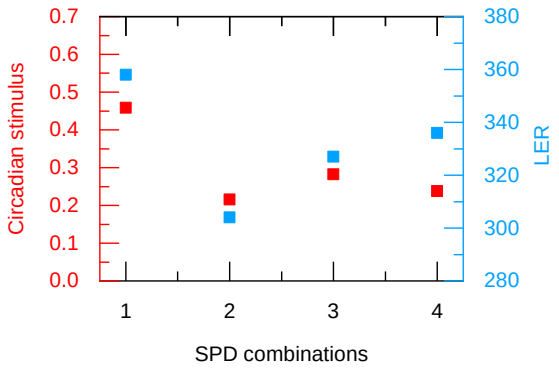

Figure 4: Circadian effect and luminous efficiency of the metameric SPDs.

two models. Considering now the visual performance as well we see though that the CRI of the two SPD is very low with a value of 58 and 48. As office lighting has a standard of minimum 80 this would result in unacceptable lighting solutions. The colors rendering will be below of what will be visually acceptably. Setting a restriction of CRI above 80 results in the SPD 3 and 4. The difference of their CS is below 0.05, or melatonin suppression of 5%. It can be assumed that in application this is negligible difference.

A widespread assumption is that only light sources with broadband spectra (comparable to sunlight) can have good color rendering properties. Therefore it is interesting to point out that the presented SPDs have a CRI above 80, even though they are a combination of narrow band LEDs. One might argue that the CRI is not sufficient to validate color rendering properties. Using the more complex and recent metric, the IES TM-15-30, rendered similar conclusions though. The fidelity indexes Rf, are above 80. For the optimization the CRI is used nevertheless for practical reasons to keep the computation time low.

State of the art is that the main influencing parameters of light having effect on circadian rhythm are the retinal irradiance and spectral distribution. The model of CS by Rea *et al.* suggests that it is most crucial to have a high illuminance (Figure 2). Considering that humans are exposed to sunlight as well as artificial lighting, it is clear that the latter is not alternative to replace natural lighting. Even on cloudy days the retinal irradiance provided by the sunlight is several orders larger than typical light in buildings. Nevertheless there are numerous conditions where no exposure to sunlight is possible and thus the aim is to optimize the stimulating circadian effects of artificial lighting, minimizing harming effects. There are limitations to increase the illuminance of office lighting in order not to have negative effect on visual properties as glaring.

The analysis shows that it is possible to achieve a difference of circadian stimulus but only at the expense of visual performance. Thus one can conclude that one circadian lighting solution cannot combine visual and non-visual properties sufficiently, taking into account the restriction of a desired constant CCT.

The described results encourage us to consider alternative possible illumination parameters such as for example the spatial light distribution (i.e., horizontal/vertical ratios). A possible lighting

solution which illuminates two fields separately. For example a two part solution containing light distribution in near field working area of a person with high visual quality. And a second light distribution in the the peripheral part of sight. In the latter very low visual quality and it is then possible to maximize the circadian effect.

Conclusions

Light sources are widely characterized by visual performance only as the LER, CRI and CCT. Todays aim is to also positively impact the circadian rhythm of humans with lighting solution. In order to quantify the non-visual performance in this analysis we use two commonly used circadian parameters in addition to the characterization with visual parameters. We generated SPDs based on 5 colored LEDs optimizing for non-visual effects and in combination to keep a sufficient color rendering quality. The analysis showed that for a 4000 K light source a difference in the CS of above 0.2 is possible, but with only for a CRI below 60. Fulfilling office lighting standards with a CRI above 80, results in SPDs with a difference of below 0.05. Thus it can be assumed that it is not possible to create a metameric lighting solution that has a circadian effect and has good visual quality. The next step in the development for innovative light sources could thus go beyond spectral distribution of light changing the spatial distribution of light.

References

[1] S. W. Lockley, G. C. Brainard, and C. A. Czeisler, "High Sensitivity of the Human Circadian Melatonin Rhythm to Resetting by Short Wavelength Light," The Journal of Clinical Endocrinology & Metabolism, vol. 88, no. 9, pp. 4502–4505, Sep. 2003.

[2] A. J. Lewy, H. A. Kern, N. E. Rosenthal, and T. A. Wehr, "Bright artificial light treatment of a manic-depressive patient with a seasonal mood cycle," The American Journal of Psychiatry, vol. 139, no. 11, pp. 1496–1498, Nov. 1982.

[3] L. Lack and H. Wright, "The Effect of Evening Bright Light in Delaying the Circadian Rhythms and Lengthening the Sleep of Early Morning Awakening Insomniacs," Sleep, vol. 16, no. 5, pp. 436–443, Aug. 1993.

[4] D. M. Berson, F. A. Dunn, and M. Takao, "Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock," Science, vol. 295, no. 5557, pp. 1070–1073, Feb. 2002.

[5] C. Cajochen, S. L. Chellappa, and C. Schmidt, "Circadian and Light Effects on Human Sleepiness–Alertness," in Sleepiness and Human Impact Assessment, S. Garbarino, L. Nobili, and G. Costa, Eds. Milano: Springer Milan, 2014, pp. 9–22.

[6] G. C. Brainard, J. P. Hanifin, J. M. Greeson, B. Byrne, G. Glickman, E. Gerner, and M. D. Rollag, "Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor," Journal of Neuroscience, vol. 21, no. 16, pp. 6405–6412, Aug. 2001.

[7] K. Thapan, J. Arendt, and D. J. Skene, "An action spectrum for melatonin suppression: evidence for a novel non-rod, non-cone photoreceptor system in humans," The Journal of Physiology, vol. 535, no. 1, pp. 261–267, Aug. 2001.

[8] C. Cajochen, "Alerting effects of light," Sleep Medicine Reviews, vol. 11, no. 6, pp. 453–464, Dec. 2007.

[9] G. Vandewalle, P. Maquet, and D.-J. Dijk, "Light as a modulator of cognitive brain function," Trends in Cognitive Sciences, vol. 13, no. 10, pp. 429–438, Oct. 2009.

[10] A. U. Viola, L. M. James, L. J. M. Schlangen, and D.-J. Dijk, "Blue-enriched white light in the workplace improves self-reported alertness, performance and sleep quality," Scandinavian Journal of Work, Environment & Health, vol. 34, no. 4, pp. 297–306, Aug. 2008.

[11] M. S. Rea, M. Figueiro, A. Bierman, and J. Bullough, "Circadian light," Journal of Circadian Rhythms, vol. 8, no. 0, Feb. 2010.

[12] M. Rea, M. Figueiro, A. Bierman, and R. Hamner, "Modelling the spectral sensitivity of the human circadian system," Lighting Research & Technology, vol. 44, no. 4, pp. 386–396, Dec. 2012.

[13] D. Gall and K. Bieske, "Definition and measurement of circadian radiometric quantities," May 2006.

[14] D. Gall and V. Lapuente, "Beleuchtungsrelevante Aspekte bei der Auswahl eines förderlichen Lampenspektrums," 2002. [Online]. Available: `http://www.lichtundgesundheit.de/cyberlux/?p=33`

[15] C. I. de l'Eclairage, "Light as a true visual quantity: Principles of measurement CIE," 1994.

[16] "LED ColorCalculator," OSRAM, version 7.23.

[17] Y. Ohno, "Practical Use and Calculation of CCT and Duv," LEUKOS, vol. 10, no. 1, pp. 47–55, Jan. 2014.

[18] R. J. Lucas, S. N. Peirson, D. M. Berson, T. M. Brown, H. M. Cooper, C. A. Czeisler, M. G. Figueiro, P. D.

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Gamlin, S. W. Lockley, J. B. O'Hagan, L. L. Price, I. Provencio, D. J. Skene, and G. C. Brainard, "Measuring and using light in the melanopsin age," Trends in Neurosciences, vol. 37, no. 1, pp. 1–9, Jan. 2014.

[19] M. Amundadottir, S. Lockley, and M. Andersen, "Unified framework to evaluate non-visual spectral effectiveness of light for human health," Lighting Research & Technology, vol. 49, no. 6, pp. 673–696, Oct. 2017.

How Digital Lighting Will Further Revolutionize Automotive Lighting

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Abstract

With the integration of LED technology, lighting has evolved from a basic, functional feature to a distinctive feature with high-value potential in automotive. LED technology has given manufacturers the opportunity for strong differentiation via lighting design and additional functionalities. Integration of new lights sources such as LEDs, lasers and OLEDs is also enabling the realization of full electronic systems and by extension the development of advanced lighting functionalities. The main objective of these functionalities is to offer beam patterns that automatically adjust to the driving environment. Recently, the use of matrix LED systems combined with camera and image processing functions has allowed for creation of new lighting functions like adaptive front lighting and glare-free lighting. Such evolution toward full electronic systems is opening a new era for automotive lighting. In a global way, digital light represents high resolution front lighting systems which offer the possibility to develop new functions, to increase road safety and driver's comfort, and make automotive lighting more intelligent. This trend of digitalization is supported by the development of autonomous driving as lighting could serve as a communication tool with the environment of the car.

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Automotive lighting: a fast growth thanks to wide LED adoption

Since the first full light-emitting diode (LED) headlamp was introduced in 2007, LED technology has gradually penetrated headlamp design. LED technology has allowed lighting to become a distinctive feature and enabled innovative functions like the glare free adaptive high beam introduced in 2013. LED technology use had been limited to high-end vehicles and has had to compete with traditional light sources, namely halogen and high-intensity discharge (HID/Xenon). Improved LED performance, lower power consumption and flexible design were the first enablers. Then, cost reductions helped LED technology spreadto all vehicle categories.

In this context, the automotive lighting market totaled $25.7B in 2016 and is expected to reach $35.9B in 2022 at a 5.7% compound annual growth rate (CAGR 2016–2022). In 2017, the automotive lighting market should be close to $27.7B. This growth is driven by natural LED cost erosion, increasing the LED penetration rate. Standardization of LED modules and their optimization are key factors behind decreasing costs. This has resulted in more vehicles equipped with LED technology.

Automotive lighting is driven by exterior lighting and especially headlamps, generating more than two-thirds of the total market revenue. Rear lighting is the second largest area, representing 17% of total market revenue. Interior lighting represents almost 10% of revenue but growth is expected to be linked to the development of autonomous vehicles and the creation of vehicles as “living homes”. Other types of lighting, such as fog lamps, Center High Mounted Signal Light (CHMSL) or small lamps, comprised the remaining 7% of revenue in 2016.

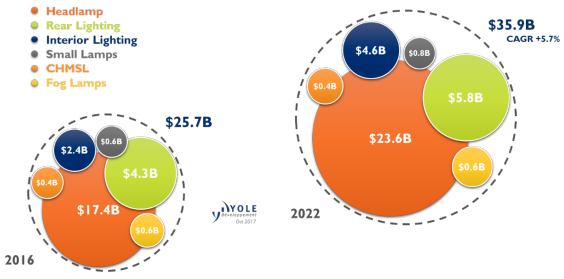

Figure 1: Automotive lighting market forecast 2016–2022.

Front lighting systems: the pixel era has just begun

Since the early 2000s there has been strong interest in new automotive front lighting functionality to increase safety and differentiate car manufacturers. The main objective of these advanced front lighting systems (AFLS) is to offer headlamps with beam patterns that adjust automatically to the driving environment according to factors including vehicle speed, oncoming traffic, pedestrians, animals, weather and cut-off lines. The emergence of such systems has only been possible thanks to front cameras that monitor oncoming traffic. Since then, systems have become increasingly complex and require the integration of electronics and software to improve the driver’s visibility at night.

Glare-free adaptive headlamps were made possible by the development of LED matrix systems splitting the front beam into up to 25 vertical segments. Such systems add value by keeping the high beam enabled even when there is oncoming traffic and therefore increasing the driver’s night visibility.

Advanced functionalities can be obtained by associating a camera and a matrix headlamp. The system is able to blank out lights that would dazzle oncoming traffic or vehicles ahead. Other possibilities are dimming lights when traffic signs are detected, marking pedestrians with a spot light or adapting the beam pattern according to external conditions such as weather, speed and road type. The first generation of matrix LED technology had up to 25 vertical segments. The second generation — commercially available in the Mercedes E-class — increases the resolution up to 84 pixels, enabling a more precise light distribution. This is the beginning of the pixel era in automotive lighting and much higher resolution will be achieved at short to medium term. All these technologies are different but they have the same objective: create new light functions such as roadway marking, driver support or pedestrian interaction.

The main purpose of lighting will no longer be the best visibility for the driver. The focus will become communication with the environment of the car. Many concepts and proposals have been made for autonomous vehicles and concerns include safety and acceptance by pedestrians. New lighting technologies can enable this interaction but standards and regulations have to be defined.

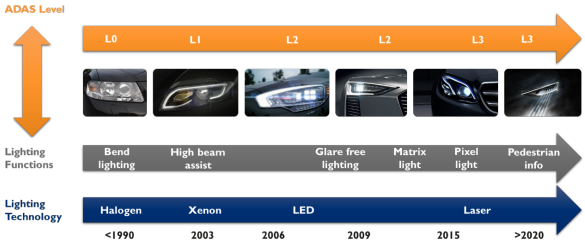

Figure 2: Relation Between Advanced Driving Assistance Systems (ADAS) and Lighting Technologies.

Current trends and development of digital light

In a global way, digital light represents high resolution front lighting systems which offer the possibility to develop new low and high beam functions, to increase road safety and driver's comfort, and make automotive lighting more intelligent. Additionally, this trend of digitalization is supported by the development of autonomous driving (i.e., ADAS) as lighting could serve as a communication tool with the environment of the car (e.g., car-to-pedestrian communication. . .).

Future developments will use micro LEDs, laser or even liquid crystal displays (LCDs) as light sources. All these technologies are in development with resolutions ranging from 2,000 pixels to more than 500,000 pixels per headlamp. Car manufacturers and their tier-1, tier-2 or tier-3 manufacturing partners are developing technologies that have never been seen in automotive lighting. Osram has built a package including 1,024 individually controllable light points. Hella and Porsche are using an LCD light source combined with dies embedded in a printed circuit board (PCB). Audi is working on lasers combined with micro mirrors.

These new technologies will offer drivers high visibility. However, because autonomous vehicles are expected in the medium term, the main purpose of lighting will no longer be the best visibility for the driver. The focus will become communication with the car's environment. This means that the car will need to interact with non-automated cars and pedestrians. The complexity of the information should be low, and the meaning should be unambiguous and clear. High-definition lighting systems are one way to do this, but a lot of research is needed to define the right signal in any situation and increase safety. Afterwards, standardization and even marketing for the new information and safety signals will be necessary. The need for standards and regulation will be essential in the development of autonomous cars.

Figure 3: New functionalities for HD lighting systems.

Conclusion

Today, digital lighting is a key area of investigation for the automotive lighting supply chain as it represents the future of automotive lighting, but several barriers have still to be overcome (e.g., technology, manufacturing, regulation. . .). Those challenges will be reinforced as digital light will even more increase the relation between lighting, automotive sensors and data processing.

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How to Solve Increasing Challenges in LED Luminaire Production

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Abstract

Recent studies show LED penetration in general lighting to be 60%–100% depending on the region and application. This presents luminaire manufacturers with a challenge. LED technology is standard and therefore no longer a special sales argument for the luminaire. Increasingly, it is price that plays the decisive role, and this raises the question of which manufacturers are in the best position to emerge from this price war stronger than before. It will be those who are continually improving their luminaires and increasing their production efficiency.

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Introduction

In the old fluorescent world, where tubes and lampholders were still basic elements of a luminaire design, the production process was based on standardised components. Standardisation is always a good basis for optimising production processes, whether they are automated or not. With the introduction of LEDs, this approach was no longer applicable for many lighting products. Suddenly luminaire designers had a degree of freedom which was previously undreamt of. This was because a luminaire no longer had to be constructed around a fixed light source. Indeed, an LED-based light source can be adapted to nearly any form of luminaire and this has resulted in a large number of new developments.

However, it is precisely these design advantages which have led to a more complex manufacturing setup, forcing production planners to introduce more flexibility in production, for example by establishing more manual workstations. Requisite processes range from setting the right output current for an LED driver, correct placement of LED modules and associated optics, through to the final product test. The latter no longer only involves testing electrical safety. In addition to functional testing of each individual LED, the colour temperature of the entire luminaire has to be validated. The final test gets really tricky when a sensor or communication unit is part of the design.

The question, looking back at the old days, is how to restore efficiency to the production process and, in response to price pressure, how to try and integrate automated production processes.

Automation

Automated production is a wide field. Requirements and investments are very dependent on the product type, quality level, number of product variants, planned sales figures and anticipated return on investment. On closer examination, it is necessary to differentiate between semi- and fully automated production. “Fully automated” indicates a production process which takes place without the direct intervention of a person. The term “semi-automated” describes processes in which part of the work is carried out manually and other parts by automated systems or by interaction between man and machine.

Automation should always be an aim when large quantities are involved or when the time required for manual work is too great. In many cases it is advantageous to use standardised components, for example to enable the use of gear trays which do not have to be set up or which can access all important positions easily. This can simplify the whole automation process considerably. This is not always practicable, of course, but when the objective is to increase productivity, the pursuit of the DSA (Designed for Automation) principle may prove to be a suitable solution. And, as a positive side effect: It is not just by chance that luminaires designed for automated production also simplify manual assembly.

DSA does not only apply to the luminaire itself, however. It must also be possible to process the relevant components automatically. This includes solutions for fixing components, the electro-mechanical interfaces and the connection technology for automated wiring.

Assembly Steps

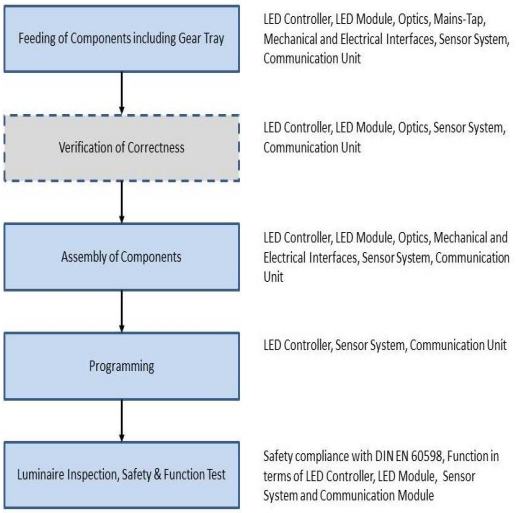

Figure 1: Assembly Flow of an Automated Production.

In general, the design of an automated production line includes all the stages listed in Figure 1. Additional tasks might be the automated filling of feeder stations or the packaging and dispatch of products after the final luminaire test.

All automated processes require the handling of

components which can be processed within the geometric dimensions of a luminaire. If a position cannot be reached or a component cannot be used by an automated assembly station, then a manual intervention in the assembly process is unavoidable. This has to be taken into consideration in the overall analysis.

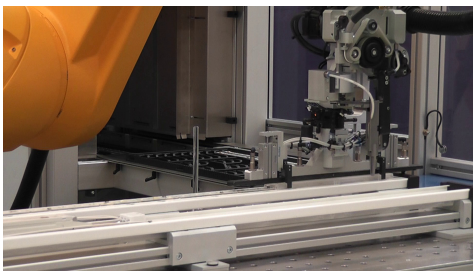

Figure 2: Linear Appl.: Automated Placement of LED Modules and Optics.

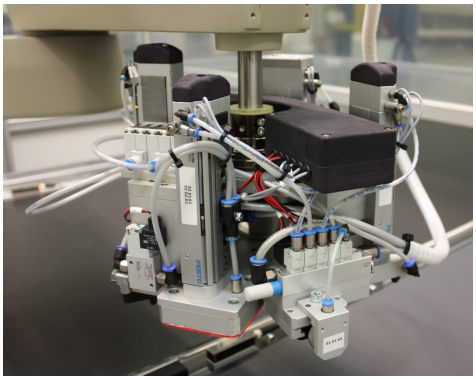

Figure 3: Spot Appl.: 4-Joint Robot equipped with a Multi-Tool-Head.

The great advantage of manual activities is their ability to adapt quickly and easily to changing conditions within the luminaire or to new or complex assembly tasks. On the other hand, one should be aware that manual work can lead to an increase in cycle time or, if the work is monotonous, to quality problems.

First proposition: If the objective is to increase productivity by reducing cycle times while, at the same time, ensuring product quality, then the luminaire design must meet the requirements for automated production. If 100% automation is unworkable due to the complexity of the processes involved, then a reasonable compromise between automated and manual activities should be found.

Handling of Components

In the past too, it was not always possible to automate all assembly work. An example is the placement of electronic control gear, which was often performed manually. The greatest potential for increasing productivity and improving quality came with the use of robot stations, which enabled the internal wiring of a luminaire and the final luminaire test to be carried out by a fully automated test station.

Today, the wiring of an LED luminaire is less complicated and error-prone. The challenges are rather to position and fix LED modules and optics. In addition, a considerably more complex system is required for the final test at the end of an assembly line.

Components for linear luminaires

LED modules and optics are generally fixed using screws and each screw requires manual intervention. One solution to improve this situation is the use of LED modules and optics which are pre-equipped with “smart” components. These so-called P2F (Push to Fix) components enable automated placement with a higher attachment quality than that provided by screws. The fixing elements are pre-installed by the supplier — in the case of LED modules, during the SMD pick&place process (Figure 4 & 5), and in the case of optics, directly after the injection moulding process (Figure 6 & 7).

Figure 4: ‘P2F SMD’ to pre-equip LED modules for easier fixation.

When subsequently setting an optic directly onto an LED module, it makes sense to attach both components by means of one fixing element. In this case, the “P2F optic” is used.

As a rule, an LED board is pre-attached to the luminaire housing in order to wire it before the optic finally holds the LED board in position. A non-secured LED board can change its position when the optic is being attached, resulting in an

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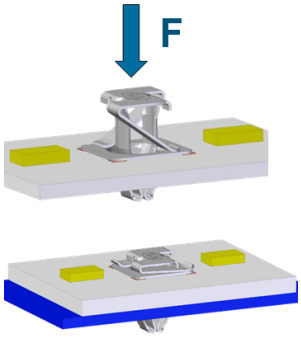

Figure 5: Usage of 'P2F SMD' in combination with PCB and luminaire.

Figure 6: 'P2F Optic' enabling the fixation of Optic and PCB.

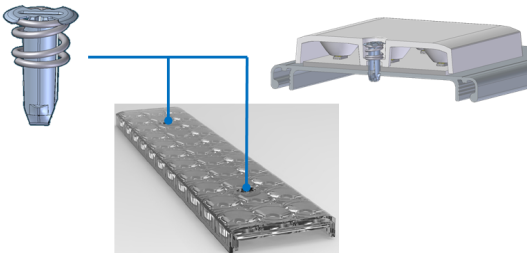

Figure 7: 'P2F Optic' in combination with Optic, PCB and luminaire.

incorrect installation in the luminaire housing. To prevent this from happening and to reduce the need for pre-attachment, it is recommended that the LED board should be picked with the optic before installation and while the LED board is still in its tray. In this way, the LED board and the optic become one unit and can be installed very easily and securely in the appropriate position in the luminaire (Figure 2). This can also be performed manually, for example by snapping the LED board and the optic together. Wiring is then carried out on the rear side of the luminaire. A "rear-side" SMD terminal block product range (Figure 8) has been developed specifically for this purpose:

A luminaire design without screws provides many more options for the automation of work processes. It is, of course, also possible to install screws automatically, but the work involved in building and maintaining an appropriate tool is

Figure 8: SMD Terminal Block for rear-side wiring 1-pole.

significantly greater than for installing technology to perform simple pick&place&fix tasks. In addition, manufacturers reduce the risk of damaging an LED board by using an incorrectly adjusted torque screwdriver. There are also the advantages provided by a "flexible" method of fixing, as this prevents the LED board from lifting off the luminaire housing due to the different thermal expansion coefficients of the materials used.

Components for spot/downlight luminaires

For assembling spot/downlights, luminaire manufacturers also have the option of using a P2F element for securely connecting the heat sink, TIM foil (Thermal Interface Material), COB and COB connector. Pre-assembled COB connectors can be attached to a heat sink very easily by means of the "P2F blind hole" (Figure 9).

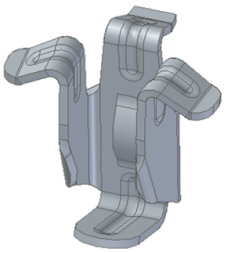

Figure 9: 'P2F Blind Hole' to pre-equip COB holders for easier fixation.

By using a robot equipped with a multi-handling tool (Figure 3), all necessary components (such as TIM, COB, etc.) can be joined together very effectively (Figure 10).

Second Proposition: A luminaire design without screws can convince luminaire manufacturers to return to automated assembly without them having to lose the degree of luminaire design freedom gained through using LEDs. With regard to fixing electronic control gear, there are still possibilities for extending the product range

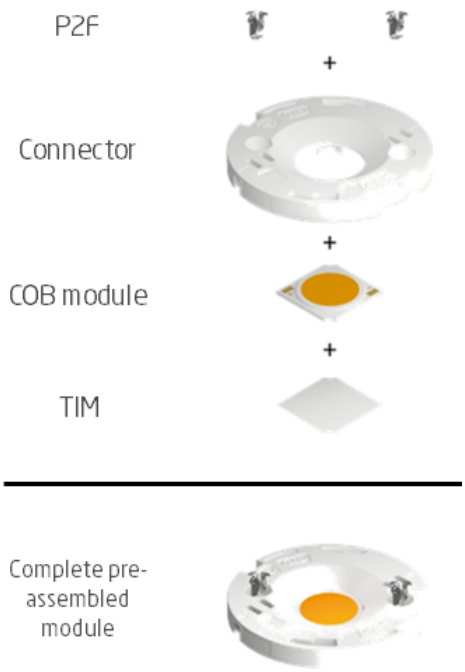

Figure 10: Usage of 'P2F Blind Hole'.

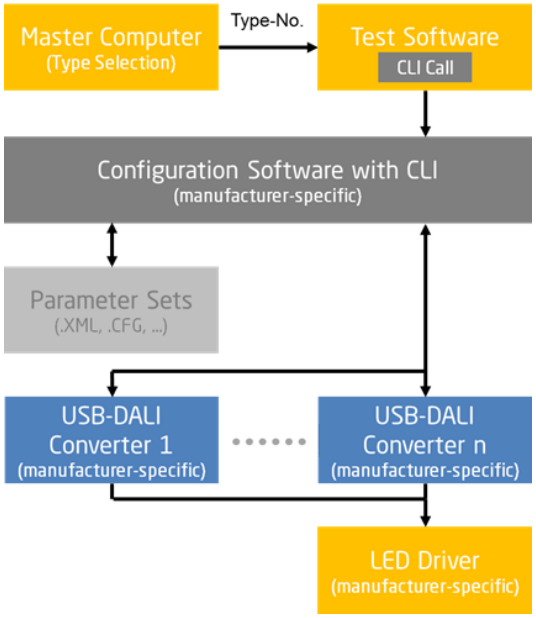

Figure 11: DALI Programming of ECGs.

for "smart" components. At the moment, however, the form factor and the weight of these components are making it difficult to find an optimum solution.

(Final) Luminaire Inspection

It is not only the assembly process for LED luminaires which has become more complicated. The final luminaire test no longer consists only of tests for electrical safety and a simple functional test. Now it is equally important to test the function of each individual LED and ensure the correct colour temperature of the luminaire. In addition, it is necessary to set the right output current and possibly other parameters on the LED driver.

Previous familiar techniques for setting the output current were to insert an external resistor or to employ data exchange via a DALI interface (Figure 11). In addition to the setting of the output current, use of the DALI protocol enables the dimming level to be adjusted in emergency situations, the output current to be increased over the service life of the luminaire (Constant Lumen Output, CLO) or the mixture of cold- and warm-white light in 2-channel applications.

Although DALI is familiar as a standard, every manufacturer of control gear offers his own hard- and software for programming his drivers. This situation has led to a very complex system of programming stations.

When using multi-watt LED drivers, setting the output current still has the highest priority. Inserting an external resistor is quite a simple task, but the use of many different resistors involves additional logistical effort for the luminaire manufacturer. Here, the DALI interface is more flexible. However, not all control gear has this kind of programming interface. In addition, an LED driver requires a mains voltage supply for programming purposes.

A new approach is the use of Near Field Communication technology (NFC) for exchanging data between a PC and an LED driver (Figure 12). This involves the use of a so-called NFC reader. The major advantage over DALI is that the driver no longer has to be supplied with mains voltage for programming purposes.

The modification of a driver can be carried out at any point on the assembly line provided the distance between the driver and NFC reader is sufficiently short to ensure the wireless exchange of data. With the harmonisation of this programming interface by the MD-SIG (Module-Driver-Special-Interest-Group), luminaire manufacturers only have to use one item of hardware, which will communicate with the respective programming software (driver-manufacturer-specific). This will considerably reduce the complexity of future

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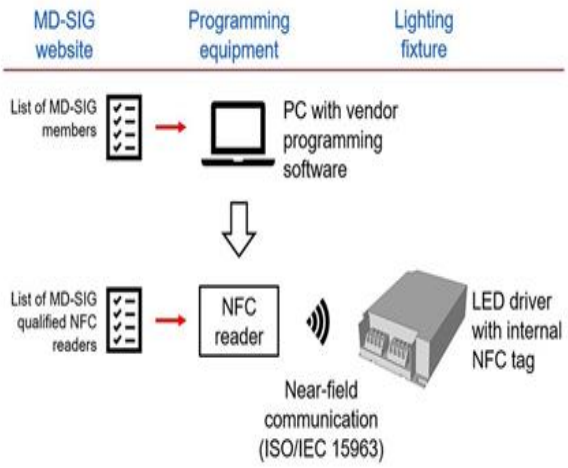

Figure 12: NFC Programming of ECGs [1].

programming stations and simplify integration into automated production lines.

Other important lighting parameters, such as the correct functioning of LEDs, verification of colour temperature, light intensity or light distribution curves can also be part of a final test. For many of the characteristics listed above, there are now high-performance camera systems available (Figure 13). However, luminaire manufacturers should bear in mind that tests for every further characteristic will lead to an increase in cycle time and will mean a considerable amount of extra work for the test station. At present, for example, it is not possible to test light distribution curves in an automated production line at economically acceptable costs.

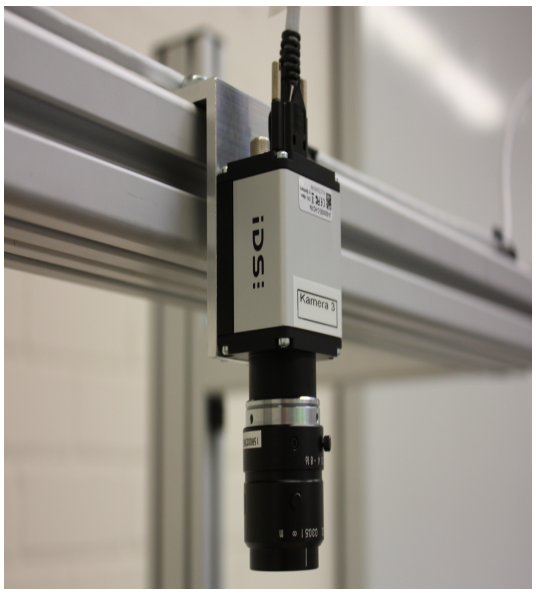

Figure 13: Optical check of luminaries.

In practice, therefore, the final luminaire test should be reduced to the necessary electrical safety tests and simple functional tests. Instead of investing in complex test structures, it is better to implement additional internal logistics measures to ensure that the correct components are delivered to the assembly line feeder stations at the right time. By reading QR codes (e.g., on the trays of LED modules), the feeder stations themselves could already determine the correctness of components, thereby supporting the assembly process and streamlining the final luminaire test.

Third Proposition: A well-thought-out chain of inspection tasks (position in the assembly line and type of test) will lead to shorter cycle times, bearing in mind that some tests have specified time frames. Also, a reduction in the complexity of the final luminaire test will ensure a better-coordinated assembly procedure.

Conclusion

Automated production can make again the difference in achieving a better margin compared to products produced with a high amount of manual work involved. Future trends in luminaire design will probably follow European guidelines aimed at producing sustainable lighting systems and reusable components. This approach requires modular lighting structures and will accelerate the development of components which are easy to attach and easy to release again. Then, assembly models involving “smart” components in conjunction with automation will probably be the only possibility for increasing productivity in luminaire manufacturing.

References

[1] http://md-sig.org/specifications/

Can the Success of OLED Displays be Transferred to Lighting?

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Abstract

Despite great success in the market for high-end cell phone displays, OLED technology has yet to achieve significant entry into the general lighting market. This is mainly due to the relatively high cost, but also caused by manufacturing problems in achieving the innovative form factors promised in concept papers and prototypes. Although steady progress is being made in device performance and fabrication techniques, the production of exciting new products at affordable prices remains challenging. This talk assesses the progress in commercialization and discuss the obstacles that remain to achieve high-volume sales.

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Introduction

Superior picture quality has led to a rapid increase in the adoption of OLED displays in both cell phones and high-end TVs. Global revenues in 2017 were about $22B (billion) and are expected to increase to over $50B in 2022 [1]. Display Supply Chain Consultants (DSCC) estimates that due to investments of over $65B in new equipment over the past three years (2016–18), the input capacity for OLED panels will increase to around 20M (million) square meters in 2019 and 35M square meters in 2022. These forecasts reflect an average selling price of 1500 $/m^2 in 2022.

The growth has not been uniform. Slowing sales in the first half of 2018 led Samsung to cut back production to less than 50% of capacity. Part of the problem arose from the relatively high price of flexible panels, which now account for more than half of new capacity.

It has been difficult to obtain reliable data on sales of OLED lighting panels. However, Business Korea has reported [2] that sales by the leading supplier, LG, in 2017 were around 10 billion Won ($9M), suggesting that total global sales were below $15M, and so less than 0.1% of OLED display sales.

The success of OLED display technology brings potential benefits to lighting applications.

- Suppliers of organic materials have responded to demands for improved performance by display manufacturers, particularly with respect to operating lifetime and color gamut.
- As demand grew, suppliers of equipment and materials were able to reduce their prices.
- The focus on flexible panels opens the possibility of ultra-light conformable panels in luminaires
- The aggressive advertising of OLED displays has made potential customers of OLED lighting more receptive to the new technology.

The main purpose of this paper is to see to what extent these benefits can be transferred to lighting. In this regard, it is important to recognize that different characteristics may be important in the two applications

Performance

Operating Lifetime and Stability

The life expectancy of cell phone displays has been relatively short, despite the high price of the leading models. However, material degradation has still been a major challenge, since relative changes in intensity of only a few percent can lead to “burn-in” of often-used patterns or color shifts. The stability of highly efficient phosphorescent blue materials has not yet reached the levels at which they can replace the traditional fluorescent sources.

In lighting, a typical requirement is that the intensity remains above 70% of its initial level for around 50,000 hours. Since degradation depends strongly on current density, manufacturers have been able to reach their targets by introducing stacked structures in which more than one photon is created for each electron-ion pair emitted from the electrodes. However, insufficient progress has been achieved in the stability of efficient blue materials, despite intensive research on several approaches.

Much attention has been paid to the encapsulation of flexible panels, since OLED materials are extremely sensitive to oxygen and water. Development of the appropriate materials and equipment has been successful, but the costs are far too high for most lighting applications.

Color Balance

The frequency spread in OLED emitters is broader than that in inorganic sources. This may be a disadvantage in displays, but is usually beneficial in lighting. The long infra-red tail of red OLED emitters leads to lower efficacy, but progress has been made on narrowing the emission profile.

The relatively low efficacy of blue emitters means that it is easier to produce white light with lower color temperatures than in inorganic LEDs. Although concern about the health effects of blue light has often been over-emphasized, the growing preference for white light with minimal blue content favors the use of OLEDs. Most OLEDs now offer CRI around 90.

With respect to color, the major challenge for OLED lighting arises from the difficulty of dynamic color control. This has been achieved in

prototypes, either by separating the RGB emitters horizontally in stripes or pixels, or by stacking them vertically with intermediate electrodes. However, either approach adds significant cost and the additional absorption in the intermediate electrodes reduces the efficacy substantially.

Efficacy

Efficacy has not been a prime concern in OLED displays, because of the low efficiency of LCD panels, in which less than 10% of the light emitted by the backlight is used to create the final image. The rapid improvement in the efficacy of LED luminaires and the broad concern about energy savings means that high efficacy is critical in lighting applications

Although OLED lighting panels with efficacy of 90 lm/W have appeared in the LG catalogue for several years, these have been delivered only in small quantities. Most of the panels that are generally available have efficacies in the range of 55–65 lm/W. This is reduced to below 50 lm/W in luminaires, due to losses in the driver.

In December 2017, LG published a new catalogue describing products to be made on their new manufacturing line in Gumi, once again promising rigid panels with efficacy of 90 lm/W. Although mass production from this line was announced in the same month, deliveries for general lighting were not available as of May 2018. The efficacy of flexible panels remains at 55 lm/W, probably due to the unavailability of internal light extraction structures for flexible displays.

OLEDWorks has taken a more modest approach to product specs. Their Brite2 panels provide efficacy of 63 lm/W at standard brightness. In the Brite3 panels, of which prototypes were shown in the spring of 2018, this will increase to 85 lm/W. OLEDWorks has also demonstrated bendable panels at 63 lm/W.

The Roadmap published in 2017 by the Solid State Lighting Program of the US Department of Energy [3] sets a target efficacy of 190 lm/W for OLED panels and 162 lm/W for luminaires. The major obstacles to achieving this are the low efficiency of stable blue emitters and trapping of the light within the device. Enhanced light extraction is particularly important for flexible panels.

Manufacturing Costs

Cost Targets

It has been assumed for at least a decade that in order to enable high-volume sales in competition with LED luminaires, the manufacturing cost of OLED lighting panels needs to be reduced to about 100 $/m^2, or 10 $/kilolumen. The DOE SSL Roadmap [3] estimated the manufacturing cost in 2016 to be about 1500 $/m^2. A path to meeting the target using traditional fabrication techniques is outlined in Table 1.

Table 1: DOE roadmap for manufacturing cost reduction.

	2016	2018	2020	2025
Substrate Area (m^2)	0.2	1.2	1.2	2.7
Capital Cost ($M)	50	125	125	200
Cycle Time (minutes)	3	2	1	0.5
Capacity (1000 m^2/yr)	17	175	350	2,400
Depreciation ($/$m^2$)	600	140	70	35
Organic Materials ($/$m^2$)	150	100	50	15
Inorganic Materials ($/$m^2$)	200	140	100	30
Labor ($/$m^2$)	100	25	15	5
Other Fixed Costs ($/$m^2$)	50	15	10	5
Total (unyielded) ($/$m^2$)	1,100	420	245	90
Yield of Good Product (%)	70	80	85	90
Total Cost ($/$m^2$)	1,570	525	290	100

Although all cost components must be reduced substantially, three items deserve special attention.

Equipment Depreciation

The key to reducing depreciation cost lies in increasing throughput while achieving high yield. Table 1 assumes that this will be accomplished by some increase in the substrate size, although this raises the cost of the equipment and leads to greater challenge in assuring high yield. Reducing the processing cycle time is also needed, but this has proved to be difficult. The previous LG line at Ochang was designed for a cycle time of 2 minutes, which would allow processing of up to 15,000 substrates per month, but the best that was achieved was 4000 sheets per month. The new line is also designed with a monthly capacity of 15,000 sheets, but it remains to be seen whether this will be accomplished.

Many believe that roll-to-roll (R2R) processing offers the best route to higher throughput. Although this approach may reduce the time needed to transfer the substrates between processing tools, the time taken for each process must be synchronized and reduced substantially from current values.

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Organic Materials

The increased demand for OLED displays has led to steady reduction in the cost of the active organic materials. However, the complexity of OLED structures has also increased through the introduction of multi-stack structures. DSCC estimates [4] that the total cost of organics in the TV displays manufactured by LG is now 130 $/m^2 for 17 layers deposited by vacuum thermal evaporation. The level of complexity is similar to that used by LG and OLEDWorks in lighting panels. DSCC expects that the average cost of organic materials for all applications will decrease from about 80 $/m^2 in 2018 to 60 $/m^2 in 2022.

It seems unlikely that the cost of materials for lighting could be substantially less than that for displays. Manufacturers other than LG may not be able to negotiate such good terms as the high-volume display makers. Also, if different materials are needed in lighting, suppliers will need to recover the costs of the additional R&D. Increased efficacy could reduce the amount of material needed and eroding the dominance of the leading suppliers could also lead to reduced costs.

Other Materials

Developers of OLED lighting have hoped that less expensive alternatives could be used as a replacement for the specialized glass used in displays. However, the cost of treated plastic or metals for substrates has remained high and encapsulation requires expensive equipment. Although the cost of transparent electrodes has been reduced substantially in the past decade, they are still too costly for lighting applications, and it is too soon to have confidence that effective light extraction enhancement structures can be manufactured at affordable prices.

The importance of the cost of structural materials is illustrated clearly by the OLED displays produced for cell phones. DSCC reports [1] that the average price charged for a flexible OLED panel of 15 cm diagonal size is about three times higher than that for a rigid panel ($83 versus $27). This price corresponds to 9000 $/m^2. It must be acknowledged that OLED displays include many elements that are not required in lighting applications, but the size of the premium demanded for flexibility is worrying.

Market Development

Despite the clear interest that has been generated among lighting designers and potential customers, the marketing strategies pursued by many of the OLED lighting producers have been counter-productive and the disconnect between concept development, prototype demonstration and volume production has been disastrous. Fortunately, such behavior has not been universal. OLEDWorks has been careful in not raising unrealistic expectations and Osram has been clear that their short-term product plans are focused on automotive lighting.

As an example, Konica Minolta was a pioneer in R&D on OLED lighting panels, reporting laboratory devices with efficacy of 139 lm/W back in 2014 [5]. At the same time, they showed highly flexible prototypes and claimed a capability for color tuning. They also constructed an R2R manufacturing facility with a capacity of 1 million panels per month and forecasted that mass production would begin in the fall of 2014. They have never revealed the performance of the panels that can be manufactured in this plant and, to the best of our knowledge, no products have been offered for commercial sales.

In order to gain exposure for their technology, LG and others have focused on design competitions, “boutique” lights with specialty lighting providers and demonstrations in prestigious locations. They have had limited success in engaging with established luminaire manufacturers and have begun to establish their own distribution channels. This diversion of personnel and resources from the development and manufacture of panels has contributed to missed production schedules.

Conclusions

Since the global adoption of LED lighting is still less than 25% and luminaire manufacturing involves many companies searching for innovative products, there is still opportunity for OLED to have a significant market impact. There are several steps that the industry could take that would accelerate the availability of affordable luminaires in general lighting.

Cost reduction remains the major challenge. Major changes in approach could help — for example the OLED display industry is making substantial investments in the development of

printing techniques. Roll-to-roll manufacturing could conceivably lead to higher throughput and lower depreciation costs, but the time taken for each process needs to be reduced substantially. More thorough analyses of the costs of R2R processing are needed.

The legacy of production delays and unmet promises must be reversed. Manufacturers need to be more open about their manufacturing problems and work together to solve them, with greater cooperation both horizontally and vertically within the supply chain.

Forming effective luminaires from OLED panels is not as simple as some proponents have hoped. More work is needed on efficient drivers with appropriate form factors and in providing supporting mechanical structures. While the size remains limited and the light emitted by each panel is small, the challenges in operating luminaires with multiple panels deserve more attention.

On a more positive note, the experience for the display market shows that OLED can be successful in taking substantial market share from a dominant technology and there appears to be no insurmountable barrier to doing this in lighting applications.

References

[1] Ross Young, “SID Business Conference Overview”, May 2018

[2] Cho Jin-young, “LG Display Produces 5th-Generation OLED Lighting Boards”, Business Korea, May 24, 2018

[3] DOE SSL Program, “2017 Suggested Research Topics Supplement: Technology and Market Context,” edited by James Brodrick, Ph.D.

[4] Bob O’Brien, “Display Materials Market”, SID Business Conference, May 2018

[5] Takatoshi Tsujimura, “Flexible OLED Lighting Advancements”, Smithers-Apex OLED World Summit, 2014

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Total Lighting Efficiency: Think Outside of the Chip

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Abstract

When you think about efficient lighting the first thing that comes to mind (and often the only thing) is the efficacy of the LED. However, as LED efficacy improvements are nearing diminishing returns of optimization, what will enable the next generation of significant improvement? The 'Race to the Bottom' for LED manufacturers leaves it up to lighting system manufacturers to develop the technologies necessary to create the next level of improvements required for a healthy industry.

Advancements in the methods that integrate LEDs into lighting solutions will open new opportunities for improving efficiency, enable innovative form factors and introduce new functionality for SSL solutions. The delivery of light, the integration of the package it is housed in, the connectivity, and the flexibility of the form factor will all become significant contributors to the overall efficiency of SSL solutions. In conjunction with these integration advancements, a more holistic approach to design, engineering and manufacturing will enable better lighting solutions of the future.

An approach to quantify the total lighting solution efficiency and effectiveness will be presented. A case study will then be shared which highlight how these engineering tools enable innovative lighting solutions when used in conjunction with advancements in integration and higher levels of collaboration within the solution team.

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Introduction

Purpose

According to the United Nations Environmental Programme (UNEP), approximately 15% of the electrical power used globally is consumed for the purpose of lighting [1]. Significantly improving the efficiency of lighting systems would, therefore, help drive essential environmental and economic goals. Although, the lighting industry has demonstrated a dramatic trend recently in improving the efficiency of the light source, the forecast shows that this trend will not continue indefinitely. as LED efficiencies are beginning to reach their theoretical maximum.

By expanding the focus beyond LED and luminaire efficiency improvements, the lighting industry can continue to drive reductions in power consumption while providing quality lighting solutions. The following proposal describes an extended set of tools and metrics that can help continue to drive down power consumption. These extensions include the application factors of light delivery and light distribution. By including these factors and a method to quantify them, additional reductions in power consumed by lighting can be realized.

History of Improvements

The history of lighting efficiency improvements has been primarily based on improving the conversion efficiency from the energy source to visible light, and secondarily, based on the efficiency of extracting the visible light from the system that converted it. This effort has extended from candles to LEDs and includes oil lamps, incandescent lamps and more. The modern driving metric for this trend is the “lumen per watt” which quantifies “power in” per “light out”.

Most recently, white LED technology has become a dominant technology and is providing another step function of improvement in lighting efficiency. Though LED efficiency started out at only a few lumens per watt, its efficiency quickly grew to well over 200 lm/W [2]. This recent trend is shown against the historical trend of traditional lighting technologies in Figure 1.

The major source of this improvement trend has been based on technological advancements within the LED itself, and although having this trend continue forever would certainly be nice,

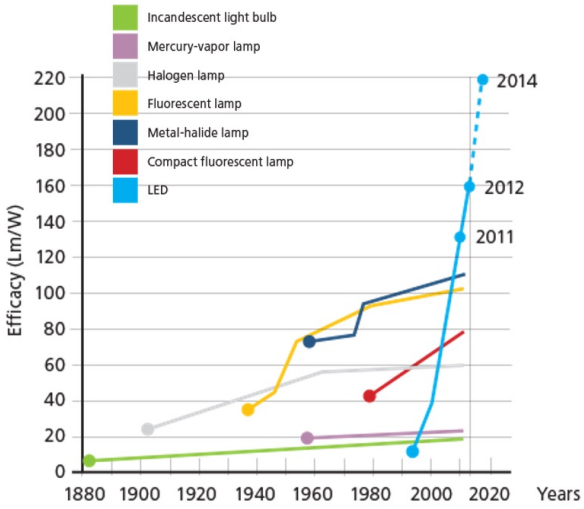

Figure 1: Historical Lighting Efficiency Trend [3].

there is a theoretical limit to how efficient the LED can be. Experts have estimated that LED efficiency will asymptotically approach 250 lm/W while their forecast shows the improvement trend dramatically slowing down year over year as shown in Figure 2.

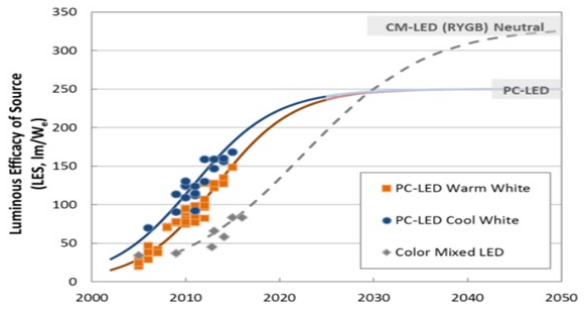

Figure 2: LED Efficacy Trend [3].

To continue reducing electrical consumption for lighting, new avenues need to be considered. As proposed here, one area of opportunity is in regards to how lighting systems are configured to disperse light within the application. By continuing to develop analysis tools, add quantifiable metrics and increasing industry focus, additional energy reductions can be made within many applications. The following proposal outlines this area of the lighting system, defines some new analysis methods and describes some approaches to optimize for the metrics.

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Defining the Lighting System

The Lighting System

As show in Figure 3, a complete lighting system includes; energy delivery, energy conversion to light, light extraction, light delivery and light distribution. The first three elements are well defined and together make up a metric called "Efficiacy". The second two are known by lighting designers, however, they are not regularly factored into efficiency improvement forecasts as they are difficult to quantify and have not been viewed as a significant driver. To address this, the next couple sections are aimed at proposing methods that more consistently quantify the delivery and distribution elements of a complete lighting system.

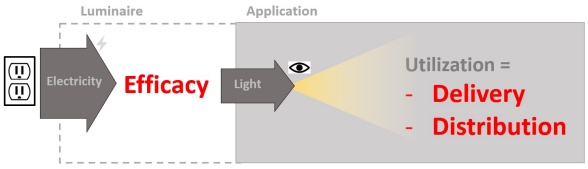

Figure 3: Complete Lighting System.

Intended Illumination Pattern

One of the most critical steps in developing and analyzing a lighting system is to define the ideal intended illumination pattern. This step is typically completed by lighting designers and experts of the application. The two most important aspects are to define the physical dimensions of the target plane(s) as well as to define the required pattern of light intensity on the specified target plane(s).

Defining the target plane(s) can be simple, complex or anywhere in between. For example, defining a rectangular target plane positioned directly under a lamp can be as simple as documenting the length and width of the target plane in conjunction with the height of the lamp above it. More complex lighting systems, however, could involve multiple non-planar surfaces in three dimensional space along with one or more light sources positioned throughout the application space.

Once the spacial dimensions of the target planes are determined, the intended light intensity pattern(s) need to be defined. Once again, this could be anywhere from simple to complex depending on the application. For example, this could be as simple as defining a single illuminance value to be homogeneous on a specified target plane. Although in many applications, a homogeneous light pattern is preferred, there are also applications where variation in illuminance on the target plane(s) can be more ideal.

Documenting the intended illuminance pattern is typically done by specifying illuminance values at specific points on the target plane(s). For the purpose of this proposal, the intended illumination pattern will be documented in the form of a matrix and referred to as $I_I(i, j)$. Where i and j are matrix points that represent locations on the specified target plane.

Independent of how simple or complex the system is, defining the light targets and intended illuminance pattern(s) is an important step. Defining these not only helps the designer communicate what is required, but can also be used as a baseline in determining the overall useful efficiency of a lighting system.

Although it is beyond the scope of this paper to go into detail about how target planes and ideal illuminance patterns are determined, it is noted that this is generally defined by the application's lighting expert in conjunction with case studies of users in the application. Additionally, this should include all areas that are intended to receive any level of light from the light source.

Based on the Intended Illumination Pattern $I_I(i, j)$, an intended luminous flux value Φ_I can be calculated using Equation (1)

$$\Phi_I = \sum_{j=1}^{m} \sum_{i=1}^{n} I_I(i, j) dA \qquad (1)$$

Light Source

Once the target plane(s) and intended illuminance pattern $I_I(i, j)$ requirements are defined, these values can be used to estimate the luminous source flux Φ_S of the light source(s) in the lighting system. One such method for determining source flux is called the lumen method which is outlined in *IESNA Lighting Handbook* [4]. Although the method won't be detailed here, the outcome estimates the lamp's source characteristics which are important in evaluating the overall efficiency of the lighting system.

The first characteristic that is important in evaluating the efficiency is the lamp source power P_S. This value quantifies the amount of power

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going into the lighting system in *watts*. The second important characteristic is the luminous flux of the source Φ_S. This value quantifies the amount of light that is emitted by the lamp within the lighting system.

Analyzing Light Quantity

Efficacy

The most common metric used for evaluating lighting systems is efficacy. Efficacy is an important metric as it objectively quantifies how efficient a light source is at converting electrical energy into visible light. As stated before, there have been significant technological advancements in this area and the efficacy metric has therefore been a primary focus for the lighting industry.

Only two values are required to determine efficacy, which will be referred to here as E_S, and can be calculated using Equation (2).

$$E_S = \frac{\Phi_S}{P_S} \tag{2}$$

Effective (or actual) Illumination Pattern

Although the desired illuminance pattern I_I was clearly defined previously, the actual pattern that the lamp creates within the lighting system will be different. The actual pattern that is produced will be referred to as effective illuminance I_E and defined as a matrix $I_E(i, j)$.

There are many methods to determine the effective illuminance. One method is to use computer models and raytrace software to simulate a value. This can be a preferred approach when the lighting system is complex and difficult to measure. Another method is to mock up the lighting system, and measure multiple illuminance points which, for an ideal setup, would be evenly spaced throughout the target plane(s). Independent of how the values are obtained, though, the data is critical in evaluating the effectiveness, efficiency and quality of the actual lighting system.

One important value that can be derived from the effective illuminance is the effective luminous flux Φ_E [5]. This value is important as it is an input for subsequent evaluation metrics and can can be calculated using Equation (3).

$$\Phi_E = \sum_{j=1}^{m} \sum_{i=1}^{n} I_E(i, j) dA \tag{3}$$

Coefficient of Utilization

The amount of light that reaches the intended target compared to how much light was generated from the light source is an important metric and is commonly referred to as *Coefficient of Utilization* or *CU* [6] and can be calculated using Equation (4)

$$CU = \frac{\Phi_E}{\Phi_S} \tag{4}$$

This value is important as it quantifies how efficient the light transfer is between the source and the target. Since this ratio can be represented as a percentage, it can help highlight how much light is wasted in the transfer and therefore drive objective improvements in lighting efficiency.

Effective Flux Error

Understanding how much light is delivered to the the target, with respect to how much light was intended to be delivered to the target, is another important part of analyzing the overall efficiency of the lighting system. Although this type of analysis is formally less common in the industry, this value will be defined and referenced here as the *Effective Flux Error* or E_E and can be calculated as shown in Equation (5).

$$\boxed{E_E = \frac{\Phi_E}{\Phi_I} * 100\%} \tag{5}$$

Effective Flux Error quantifies, as a percentage, how much difference there is between the effective (or actual) light verses what was intended. A value of zero percent would indicate that there is no error. A negative value would indicate that the effective flux is low, and by how much. Finally, a positive value would indicate the effective flux is high, and by how much.

Analyzing Light Distribution

Overview

Up to this point, the metrics that have been defined provide a strong set of tools to evaluate the quantity of luminous flux that is being

generated and delivered to a predefined target. Most efficiency metrics that are commonly used are based on this type of analysis. Although these types of analysis provide powerful metrics for evaluating lighting system efficiencies, they don't capture the complete picture. Expanding the analysis to include metrics that qualify how the light is distributed across the target provides additional tools that can help drive efficiency improvements within a lighting system.

Though the correlation regarding why light distribution within the target would have a practical effect on lighting system efficiency may not be intuitive, the rationale is as follows. Most lighting targets are defined such that a matrix of test points need to meet a minimum illuminance value. Typically, the effective illuminance pattern I_E on the target ends up being being somewhat inconsistent with the intended illuminance pattern I_I. A two dimensional depiction of this is shown in Figure 4. In order to meet the intended requirements, the source flux Φ_S is increased until all points are above the minimum value. This approach results in a solution where much of the intended target has more light than is necessary.

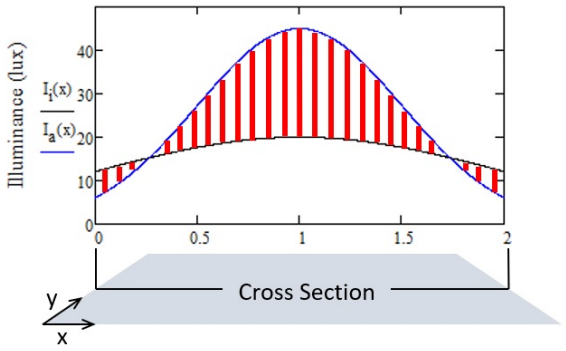

Figure 4: Illuminance Difference.

Uniformity

The most common and direct method in analyzing how well the light is distributed over the target is to quantify how uniform the effective illuminance pattern I_E is. The method for this is to calculate a uniformity value which can be done using Equation (6).

$$U_E = \frac{\min(I_E(i,j))}{\text{avg}(I_E(i,j))} \tag{6}$$

The value determined with this is often called *homogeneity* and is a value between zero and one which describes how homogeneous the illuminance is across the target. A low value correlates to high variation, where a value of one correlates to no variation.

Normalized Uniformity

Although many, if not most, applications intend for the light pattern to have continuous uniformity, there are numerous applications where a non-uniform pattern is desired. Drawing this distinction is highlighted here because it is common to directly measure effective uniformity (or homogeneity) of the effective illuminance pattern I_E as a complete metric. This approach is limited, though, as it assumes that the light pattern is intended to have continuous uniformity.

A Normalized Uniformity U_N is proposed here as a more general approach for determining how consistent a given light pattern is compared to what it was intended to be. This can be calculated by Equation (7) and represents a more general form which accounts for situations where the intended illumination pattern I_I is non-uniform. It should be noted that the traditional uniformity calculation can be considered a special case within this more general form.

$$\boxed{U_N = \frac{\min(I_N)}{\text{avg}(I_N)}} \tag{7}$$

Where normalized illuminance I_N is:

$$I_N(i,j) = \frac{I_E(i,j)}{I_I(i,j)} * \frac{\text{avg}(I_I)}{\text{avg}(I_E)} \tag{8}$$

Analyzing Useful Light

Overview

The previous sections documented existing methods of analyzing lighting system efficiency as well as expanded them into more general forms. From this set of tools a new, more encompassing, efficiency metric can be derived.

Useful Efficiency

The approach in determining this new efficiency metric is to establish the intended illuminance pattern I_I as a baseline of ideal light usage within the application. All the the light, in the actual application that is delivered up to this baseline, is then considered *useful* light. All of the other light, that is delivered above or outside of this baseline, is not considered *useful* light.

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This approach represents a shift in thinking for the experts who define the intended illuminance pattern. Typically, these patterns are defined as a set of minimum illuminance values. When discrete illuminance values in the actual application exceed the specified minimum, this is generally considered “good”. Although this is effective, it leaves room for solutions to produce wasteful levels of light and use irresponsible levels of power without being measured as such. By specifying the intended illuminance pattern as an ideal pattern, that achieves high quality lighting without being wasteful, designers and engineers can be more intentional to avoid excessive power usage in lighting solutions.

To objectively analyze the solutions that take this approach, a useful illuminance I_U can be determined using Equation (9).

$$I_U(i,j) = \min(I_I(i,j), I_E(i,j)) \tag{9}$$

The concept behind this equation is that all illuminance that exceeds the intended illuminance is discounted down to the intended value. A visual showing this deduction for the baseline solution in the case study is shown in Figure 5, where the useful illuminance pattern on the right is derived from the effective and intended illuminance patterns on the left.

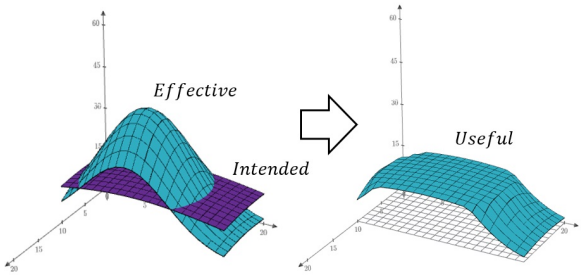

Figure 5: Useful Illuminance Derivation Example.

Based on the useful illuminance pattern I_U derived from the intended and effective patterns, a useful luminous flux Φ_U can then be calculated using Equation (10).

$$\Phi_U = \sum_{i=1}^{n} \sum_{j=1}^{m} I_U((i,j)dA \tag{10}$$

From the useful luminous flux Φ_U, a useful efficiency E_U can then be determined. This is simply done by taking the ratio of useful luminous flux Φ_U to source power P_S as shown in Equation (11).

$$\boxed{E_U = \frac{\Phi_U}{P_S}} \tag{11}$$

The value of this metric is that it quantifies the efficiency of the lighting systems ability to convert electrical power into *useful* lumens on the target based on what is predetermined by an expert to be an ideal illuminance pattern. By quantifying this as well as the steps to derive it, lighting engineers are able to further minimize the amount of power required to establish a high quality lighting system.

Automotive Welcome Light Example

Overview

Now that the preexisting and added analysis tools have been shown, a case study will be presented as a way to show how these tools work. For this case study, an automotive welcome light example has been selected as it constitutes a somewhat simple target setup, yet demonstrates the tools and optimization methods being presented here.

Welcome Light Requirements

Automotive welcome lights are small lamps, which are typically mounted on the underside of the rear view mirror as shown in Figure 6. These lamps provide ground illumination on the right and left side of the vehicle for users as they approach the vehicle in low light environments. Each lamp must provide enough illuminance that users approaching the front and rear doors, can identify ground conditions such as mud or puddles.

Figure 6: Application Example Light Source.

Given that vehicles vary in size, and specific solutions are often proprietary, a general light target was defined as being a representative aggregate, but not specific to any particular make, model, or manufacturer. The geometric dimensions of the general light target are sown in Figure 7.

Although, mud and puddles can begin to be identified at an illuminance value of about three

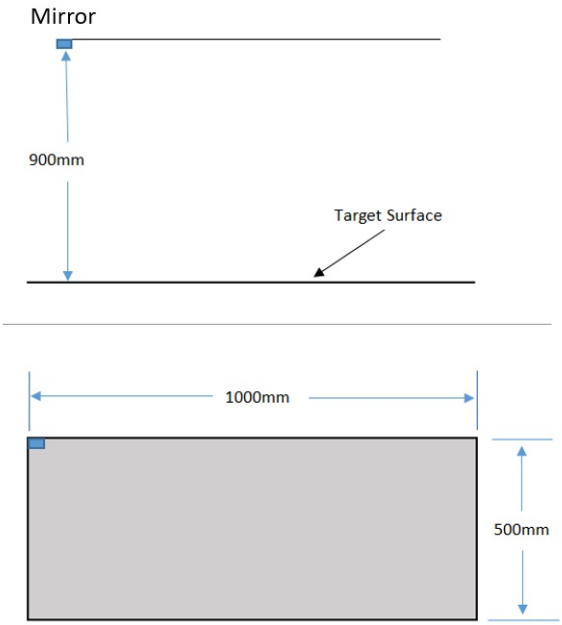

Figure 7: Puddle Target Definition.

lux, a average illuminance value of fifteen lux is defined here as preferred as it provides more definite illumination of varying objects, textures and colors on the ground.

A homogeneous illuminance pattern across the target can be a good solution. A slightly higher illuminance value in the center which rolls off to slightly lower values in the target corners is chosen for this case study, however. This pattern which is shown in Figure 8 is sometimes preferred, as the pattern tends to better blend into the environment. Though, how the illuminance rolls off outside of the defined light target is an important part of this preference, that aspect won't be detailed here.

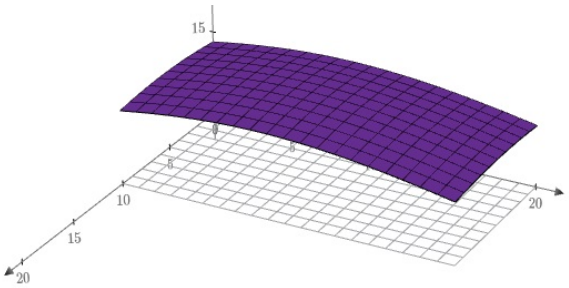

Figure 8: Intended Illumination Pattern.

Baseline Solution

Given limited space constraints in the mirror and a desire to keep the A-Surface flat, common lamp solutions are constructed using light sources that are made of an LED light panel that is positioned horizontally and with low height profiles. In this construction, one or more LEDs are aimed directly at the ground, and one or more custom lenses are placed in front of the LED(s). The lenses are positioned to focus and refract the light rearward and into the light target. This construction is shown in Figure 9.

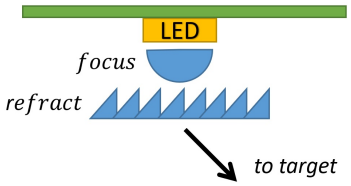

Figure 9: Baseline Construction.

This basic construction produces a roughly lambertian pattern which is ideally directed rearward in vehicle toward the far side of the target. Even when the light is aimed at the rear third of the target though, the conditions of distance and angle result in a pattern that has a hot spot in the middle to near corner of the target as shown in Figure 10.

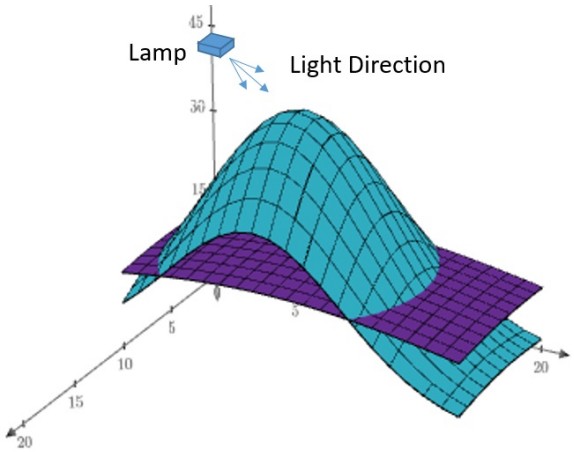

Figure 10: Baseline Illuminance Pattern.

Baseline Analysis

As shown in Figure 10, the most difficult aspect of meeting the target requirements is to deliver enough light to the far side of the target to meet the intended illuminance values. In the baseline construction, an LED source flux of 51 lm was chosen. Although this is not high enough to meet the intended lux requirements in the corners of the target, it is low enough to avoid a significant hot spot in the middle of the target. The corresponding properties for this configuration are shown in Table 1 below.

From these given and measured properties, the

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Table 1: Baseline Welcome Light Properties.

Property	Value	Units
Φ_I	7.25	lm
P_S	0.528	W
Φ_{LED}	51.0	lm
Φ_S	17.0	lm
Φ_E	10.5	lm
min(I_E)	1.76	lx
avg(I_E)	19.7	lx
min(I_N)	0.117	
avg(I_N)	0.959	

previously described metrics can be calculated. These calculated values are shown in Table 2 below.

Table 2: Baseline Welcome Light Metrics.

Property	Value	Units
Efficacy	32.2	lm/W
CU	0.553	
E_E	144	%
U_E	0.089	
U_N	0.122	
Φ_U	6.35	lm
E_U	12.0	lm/W

From these metrics a number of opportunities for improvement are quantifiably made clear. First, the Efficacy is much lower than the potential of 100 lm/W to 200 lm/W that LED lamps are capable of. Second, based on the E_E metric, it is clear that more light is being delivered to the target than is necessary. Third, based on the CU metric, it is shown that more than half of the light from the lamp is making it to the target. Fourth, based on both the U_E and U_N metrics, the light is poorly distributed across the target. It should be noted though, that because the normalized uniformity U_N is higher than the effective uniformity U_E, the pattern at least somewhat matches the intended pattern in shape, but not scale.

As a summary of the metrics, the most obvious areas of potential improvement in this lamp setup are efficacy and pattern shaping. Although this can be somewhat deduced subjectively from the simulation results shown in Figure 10, the objective metrics give a measurable baseline for improvement.

Source Optimizations

The first area of focus in improving the baseline solution will be to increase the efficacy of the lamp. On investigating the lamp, it is found that only 37% of the light from the LED is exiting the lamp which is determined to be the primary cause of the low efficacy.

The main cause of the low light extraction efficiency is that the optics require a significant amount of light redirection. Generally speaking, this increases the amount of refraction and lens surfaces needed to redirect the light which reduces the overall efficiency. In addition, the height constraints in the mirror prevent more efficient lens and reflector topologies to be used.

To address this in the improved solution, the LED will be positioned such that it is aimed in an ideal direction that minimizes the amount of light refraction and reflection required. This construction is shown in Figure 11 below. Although this will require more advanced manufacturing technologies, there are options available for this which can enable significant efficiency gains.

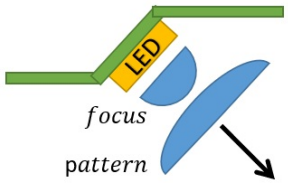

Figure 11: Improved Construction.

The next area of improvement focus will be to engineer a lens that spreads the light out over the target in a pattern that more closely matches the intended illuminance pattern. As shown in Figure 11, a custom secondary lens will be positioned and shaped as to project a significantly non-lambertian pattern. Although this will require significant engineering technical skill and powerful tools, a solution can be found which again significantly improves overall efficiency.

By applying these improvements, it was found that the luminous flux of the LED could be reduced from 51 lm to 22 lm. The resulting improved illuminance pattern is shown in Figure 12.

Although the peak illuminance value is much lower, the improved illuminance pattern more closely matches the intended illuminance pattern shown in purple below it. The properties for this solution are shown in Table 3.

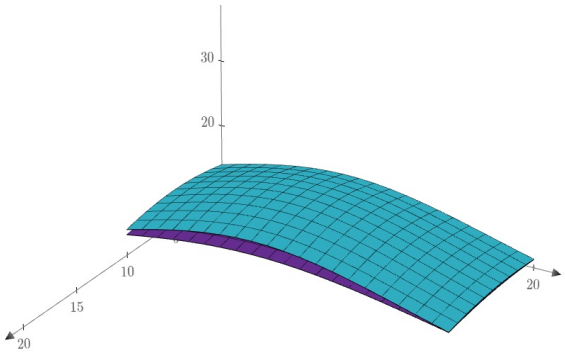

Figure 12: Improved Illuminance.

Table 3: Improved Welcome Light Properties.

Property	Value	Units
Φ_I	7.25	lm
P_S	0.229	W
Φ_{LED}	22.1	lm
Φ_S	14.7	lm
Φ_E	8.05	lm
min(I_E)	11.3	lx
avg(I_E)	15.9	lx
min(I_N)	0.903	
avg(I_N)	0.997	

From these given and measured properties, the previously described metrics can be calculated. These calculated values are shown in Table 4 below.

Table 4: Improved Welcome Light Metrics.

Property	Value	Units
Efficacy	64.0	lm/W
CU	0.546	
E_E	111	%
U_E	0.710	
U_N	0.906	
Φ_U	7.20	lm
E_U	31.5	lm/W

Solution Comparison

Reconfiguring the LED position and optics increased the efficacy by a factor of almost 200%. Although this is a significant improvement, the *useful* light on target was increased by more than a factor of 260%. Through the combination of these two improvements, the the lamp's power consumption was able to be reduced down to 43% of the initial power.

In addition to the improvements in power reduction, the lamps quality performance also increased. Though this can be seen subjectively as reduced variation in the simulation graph, it is objectively quantified by improvements in the following metrics; effective flux error E_E, uniformity, U_E and normalized uniformity U_N.

One of the key areas to highlight is that the efficiency of the LED in both the baseline and improved solutions was the same. Both solutions used an LED and driver combination that was 96.6 lm/W. Despite this commonality, the improved solution was able to deliver a higher quality pattern while using only 43% of the baseline power.

Technologies that Enable Optimizations

The need for next generation manufacturing technologies was mentioned as an enabler for the improvements made in the case study. Although not all applications require this, benefits from positioning one or more LEDs in compound angles is common. When solutions are constructed using traditional printed circuit board based approaches, achieving compound angles is difficult and expensive.

A number of alternatives to position LEDs on compound angles are available. One common solution for this is to construct the electronics using flex circuit technology and assemble it into a rigid housing which includes fixed compound planes that position the LEDs. Another unique solution is called "BoardFree(R)". In this construction, LEDs are soldered to a metal lead frame. The metal lead frame is then formed and over-molded to produce a rigid, sealed lamp. This construction allows multiple LEDs to be positioned in multiple compound angles and can be used to optimize light direction and distribution within given applications.

Conclusions

Although lighting efficiency improvement trends that are driven by LED improvements are expected to wane, efficiency improvements can be driven further by focusing on the other areas of the total lighting system. Additionally, new measures and metrics can be added to create

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common points and enable better communication between lighting designers, lighting engineers and industry experts.

One such metric presented here is the useful light efficiency metric. In conjunction with well defined intended illuminance patterns, designers and engineers are able to work together to create high quality lighting systems while minimizing the amount of power required to run it.

Finally, new lamp construction technologies should be expanded and utilized in order to help support the lighting designers and engineers initiatives to continue to drive down the power required for quality lighting solutions.

Appendix

List of Acronyms

CU Coefficient of Utilization

DOE Department of Energy

IESNA Illuminating Engineering Society of North America

LED Light Emitting Diode

UNEP United Nations Environmental Programme

Acknowledgment

The Lighting Professional Symposium facilitates an environment for knowledge sharing between all professionals in the lighting industry. Their effort helps to enable learning, collaboration and innovation which in turn accelerates the betterment of lighting systems globally.

The U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, documents LED technology trends and sets aggressive, yet attainable goals for critical components withing the SSL industry. Their efforts help to create alignment, collaboration and common objectives for lighting professionals which is ultimately accelerating the reduction of power usage for lighting globally.

References

[1] United Nations Environment Programme, "Green Paper: Policy Options to Accelerate the Global Transistion to Advanced Lighting", November 2014. [Online]. Available: http://www.enlighteninitiative.org/Portals/0/documents/global-forum/Green_Paper_FINAL\%20reduce.pdf. [Accessed May 2016]

[2] LED Academy. (n.d.). "LED Theory, 5.1 High Efficacy". [Online]. Available: http://www.ledacademy.net/5-1-high-efficacy/. [Accessed Nov 2017]

[3] U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. (2017), "Solid-State Lighting 2017 Suggested Research Topics". Washington, DC.

[4] Rea, PH. D., FIES, Mark S., Illuminating Engineering Society of North America (2000), "The IESNA Lighting Handbook", 9th edition, 8–11 to 8–14

[5] Trilux. (n.d.). "Luminaire Classification by Luminous Flux and Efficiency Method". [Online]. Available: https://www.trilux.com/in/lighting-practice/lighting-equipment/luminaires/photometric-classification/luminaire-classification-by-luminous-flux-and-efficiency-method/. [Accessed June 2018]

[6] Illuminating Engineering Society. (n.d.). "Coefficient of Utilization, CU". [Online]. Avalable: https://www.ies.org/definitions/room-utilization-factor-utilance/. [Accessed May 2018]

The Technology and Implementation of Dynamic Beam Shaping

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Abstract

Through most of the 20th century, lighting designers used beam shaping in all types of lighting scenarios. Its implementation varied based on industry and application, but it was a relatively simple endeavor. From entertainment lighting to architectural illumination, it was usually achieved by deploying large and expensive zoom fittings or by changing out one lamp for another with a different, specific, distribution. In the entertainment segment, designers still use zoom fixtures, motors, and mechanical apparatus to deliver beams as narrow as 5 degrees and as broad as 90 degrees. The large fixtures require space and power and therefore aren't suitable for commercial, retail, hospitality or residential applications.

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Figure 1: ETC Source Four Zoom.

Introduction

In architectural lighting, where down-lights, recessed luminaires, and track fixtures dominate, there are three traditional forms of beam shaping: the addition of some type of a lens or barn doors to affect the beam; changing the reflector in the luminaire; or changing the lamp. In each case, manual intervention and a ladder are required. Changing lamps has been the simplest of these methods and over time, the lamp industry developed a portfolio of six beams (very narrow spot, narrow spot, spot, flood, wide flood and very wide flood) with beams ranging from 5–7 degrees for the very narrow spot to 60+ degrees for the very wide flood. With these options, designers could create scenes in a shop or restaurant where it would remain static until the next lamp change or reconfiguration of the space.

Functionality lost and found

With the advancement of solid-state lighting, beam shaping became more difficult and architectural lighting designers, for the most part, lost their ability to easily set scenes when using LED luminaires. Though it's still possible to use accessories (barn-doors, snoots etc.) or snap a lens to the front of an LED luminaire, they are not the easiest or most common solutions. Lamp manufacturers have yet to deliver LED PAR lamps comparable to halogen or metal halide form factors, output and light quality. The dominant lighting solution is a COB (chip-on-board) light source that is integral to the luminaire leaving a reflector change as the only, yet difficult and unrealistic, option.

Lighting designers have essentially lost the once common ability to shape beams.

We suppose that some miniaturization of the entertainment industry's motors and mechanicals could enable a beam shaping solution for lighting designers, though it is unlikely that budgets, reliability and form factors could be achieved and maintained. However, work initiated a decade ago in the camera and imaging segment has evolved into a technology that once again gives lighting designers the ability to shape beams from a variety of luminaires and takes it one step further by making the function digitally dynamic. Not only can lighting designers once again easily change beams, they can do so via wired or wireless control solutions. No ladders, no changing reflectors, no lost time.

Liquid Crystal Technology

Most hear the term liquid crystal and think of liquid crystal displays (LCD) displays. While both LCD technology and Dynamic Beam Shaping technology use liquid crystal molecules, the lens is simpler, relatively inexpensive, reliable over tens of thousands of hours, and can be electronically managed.

Liquid crystal molecules naturally allow light to pass through them and the quality and quantity of light are virtually unaffected until an electric field is introduced and the orientation of the molecules changes essentially creating a focusing mechanism.

Liquid crystal materials are widely used in projectors and LC Displays (LCDs) [1][2]. Despite their confusing names, liquid crystals are simple uniform liquids (there are no crystals floating in the liquid) composed of elongated molecules that are naturally aligned in the same direction, Figure 2a [3]. The typical liquid crystal cell is composed of two glass substrates separated by spacers and sealed to contain the liquid crystal material, essentially forming a liquid crystal sandwich. The application of an external electric field [4] (e.g., by using transparent indium tin oxide, or ITO, electrodes) enables the non-uniform reorientation of liquid crystal molecules (along the x axis, Figure 2b, which in turn creates a gradient of the refractive index and focuses light along the z axis, Figure 2b [5]

This configuration can be used to achieve high-quality dynamic light control. For a qualitative comparison only, Figure 2c depicts a typical LCD (liquid crystal display) structure that is complicated

and optically non-efficient as its polarizers, color filters, and thin film transistors absorb light.

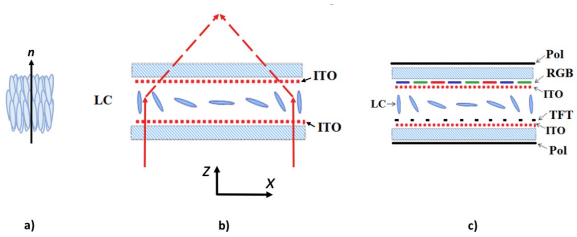

Figure 2: Schematic cross-sectional presentation of a) liquid crystal molecules that are naturally oriented in the same direction n, b) of a liquid crystal cell that can focus light. Dotted horizontal lines represent ITO electrodes. Solid vertical arrows represent the incoming light (parallel to z axis). Tilted dashed lines represent the focusing light. c) of a typical cell of LCD. Pol: polarizers, RGB: red blue green filters, TFT: thin film transistors, ITO: electrodes.

A majority of modern LED light sources generate a very large angular distribution. This distribution is typically collimated with the help of reflectors and/or special optics (e.g., Fresnel type). Such an approach typically is characterized by a relatively large beam diameter $\varnothing_0$ and large original divergence angle θ_0 (usually measured as full width at half maximum or FWHM). Thus, those sources have relatively large etendue values. This "*imaging*" design (Figure 3a) can be modified to create "*lighting*" lenses (Figure 3b) that are composed of arrays of micro lenses (spread over large enough areas, called here "clear aperture", to cover the diameter $\varnothing_0$ of the beam) that can all be activated at the same time. (Note that the segmented control is also possible in principle.)

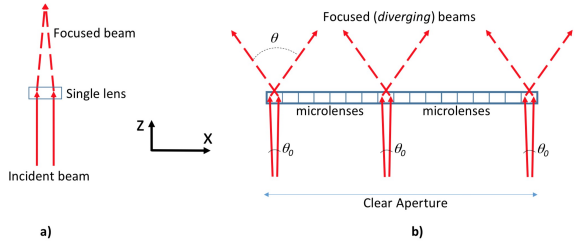

Figure 3: Schematic presentation of a) light focusing by using a single aperture (imaging) liquid crystal lens and b) Augmentation of light's divergence angle θ by strongly focusing different areas of the beam with the help of multiple micro liquid crystal lenses.

The operation principle of these "lighting" lenses is as follows Figure 3b: at the ground state, all liquid crystal molecules are aligned in the same direction and the sandwich is optically uniform. In this state, light beams propagate through the element without being angularly perturbed and, consequently, the parameters of light are not noticeably changed. The application of the electric field generates lens-like reorientation of molecules within each micro lens and the different areas of light beam become focused, which results into augmentation of the divergence angle θ of light (Figure 3b) that is proportional to the strength of those microlenses (defined by the voltage applied). It is important to note that there is neither mechanical movement nor deformation during this process.

Most light sources are not polarized[1]. The device described (in Figure 2 and Figure 3) can control only the divergence of light that is linearly polarized (along the z axis). Its use with an unpolarized light source would thus broaden half of the light while the other half of the light will be unaffected. This will generate a hot spot of light in the center of the beam since half of the light broadens while the remaining energy continues propagating straight forward. By using more than one "liquid crystal sandwich", one can achieve simultaneous control of both polarization components of light.

Optical Beam Effects

We can test and show the effect of beam shaping using the liquid crystal lens. Beam control with the lens is analog in nature as shown below.

Effect on CCT and Color Rendering

The liquid crystal lens does create a small and measurable effect on both correlated color temperature and color rendering but one that is unlikely to have a qualitative impact on the illumination scheme. Testing results are shown in Figure 4 and Figure 5. Typical impacts on R_a CRI values are very low a shown in column 1 of Figure 5.

	Color Parameters								
	CCT [K]	CRI	CIE 1931, x	CIE 1931, y	Dominant λ [nm]	Purity	u'	v'	Δuv Chromaticity dif.
No LVBS	3441	87.4	0.407	0.388	486.2 nm	0.105	0.238	0.340	0.0018
LVBS at 0V	3404	86.5	0.411	0.394	488.2 nm	0.093	0.238	0.342	0.0010
LVBS at 20V	3380	86.1	0.413	0.396	489.0 nm	0.087	0.239	0.343	0.0013

Figure 4: Typical color parameters (table).

[1] Polarized light waves are light waves in which the vibrations occur in a single plane. The process of transforming unpolarized light into polarized light is known as polarization. `http://www.physicsclassroom.com/class/light/Lesson-1/Polarization`

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Color Rendering Index (CRI) R values. (Ra calculated from R1-R8)															
	Ra	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15
No LVBS	87.4	86.9	92.8	96.2	86.6	86.6	89.9	88.2	71.9	32.9	81.9	85.8	72.6	88.4	97.7	82.2
LVBS at 0V	86.5	85.5	91.9	96.2	85.7	85.2	88.9	88.1	70.3	28.4	80	84.6	70.5	87.1	97.7	80.3
LVBS at 20V	86.1	85.1	91.6	96.2	85.3	84.7	88.6	88	69.7	27	79.3	84.1	69.8	86.6	97.6	79.6

Figure 5: Typical color rendering index.

Optical Transmission

There are 3 mechanisms of transmission losses generated by the liquid crystal lens: absorption, reflection and scattering as shown in Figure 6.

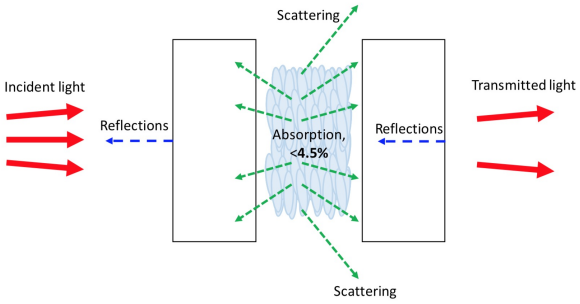

Figure 6: Schematic demonstration of 3 mechanisms of transmission losses (absorption, reflection and scattering) generated by a liquid crystal lens.

Liquid crystal materials are essentially transparent in the visible spectrum; they have absorption bands at short wavelengths, typically below 300–350 nm. The lens also has transparent electrodes and alignment layers that contribute to the light absorption. In tests, the spectrally averaged absorption of the liquid crystal lens is less than 4.5%.

Light scattering is also typically larger for shorter wavelengths and is mostly concentrated in the forward direction. However, there is also a weak but large angle scattering (see hereafter). Finally, there are reflection losses (Fresnel) from various interfaces. Just for a reference, for a visible spectral range, a typical reflection loss of a "stand-alone" glass plate is ≈ 8%.

Based on our testing of the liquid crystal lens designed by LensVector, the results for a LED luminaire and liquid crystal lens show that the loss is due to the lens is comparable to that of the cover glass. The loss introduced by the lens when it replaces the cover glass, is ≈ 6.8% at 0 V, 8.4% at 6 V, and 9.6% at 14 V. This loss is approximately composed of 4.4% absorption, 1.2% reflection (from internal interfaces) and 1.3% scattering (back and side).

It is clear that the benefit of the liquid crystal lens — Dynamic Beam Shaping — far exceed the quantitative and qualitative impact on the light.

Integration and Control

The integration of a liquid crystal lens is much simpler than the science of liquid crystals and refractive indexes. In fact, it's as simple as managing many of the warm dimming and CCT tunable LEDs solutions that have become prevalent in the last two years.

Perhaps the most important design criteria for an OEM is that the lens can be used to broaden a distribution but not narrow it. For this reason, one must start with a collimated beam from the source and secondary optics. If the initial beam is 10 degrees, then it is possible to expand and contract the beam, but not below the original size of the beam.

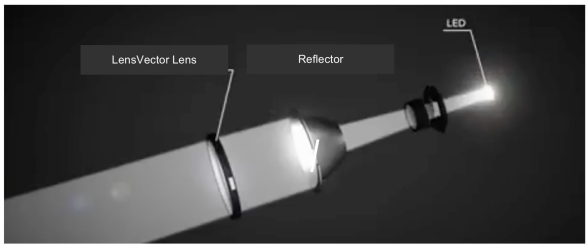

Figure 7: Courtesy of Targetti.

Assuming a narrow beam to start, the lens itself can be integrated into the fixture quite simply (Figure 7. In the case of a LensVector lens, this means accommodating a 48 mm or 65 mm lens and the connections for power and control, two of each.

From this perspective, integration into a luminaire is straightforward and not significantly different than incorporating an optically clear piece of glass as many OEMs do today.

As described earlier, the power requirements are minimal and easily supplied by today's drivers. Like other functions, including dimming, CCT tuning, etc, control functionality is required in addition to power. There are two common designs for providing this functionality. The first as shown below in Figure 8. A power transformer feeds DC power to both the LED Driver and the Lens Function (or dimming or CCT tuning). From the combined driver/function 'box' power and control signals are sent to the LED and lens.

The lens function provides the correct variable

amplitude square wave (VASW) that is used to control the focus and the lens' dynamic beam shaping.

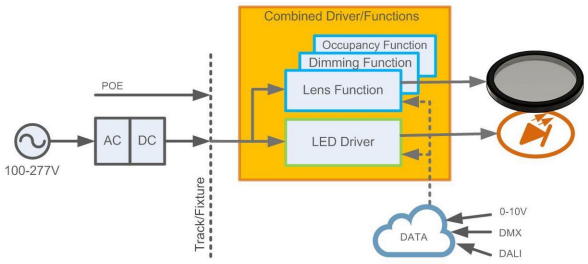

Figure 8: Power and control schematic for LensVector's dynamic beam shaping lens. This approach is currently used by companies including LEDRA and Targetti.

Other than receiving the correct control signal, the lens itself is agnostic to the wired or wireless control system. As shown in both figures x and y, the lens itself is a functional step away from the control interface that is used and is therefore agnostic with respect to control, leaving it to the OEM and lighting designer to determine whether control will be wired or wireless and what protocol may be used.

Another power/control option is shown in Figure 9. In this case, the power supply is integrated with the LED Driver and Lens Function. This is the structure commonly supplied by companies including TCI, Tridonic, Osram, and Meanwell, and simply incorporates the power supply with the driver and lens function.

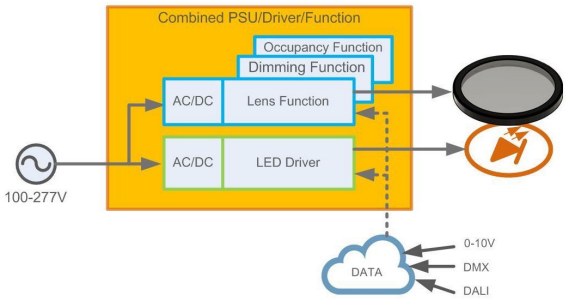

Figure 9: Integrated power supply and lens function.

Establishing standards in rapidly changing technology environments is notoriously difficult and this has proven true in the control solution segment of the lighting industry which Is littered with acronyms including WiFi, BLE, WMN, DALI, 0–10 V, DMX, and POE. The selection and use of a luminaire with Dynamic Beam Shaping does not drive the selection of any particular control solution. In fact, the lighting designer is free to select the system that works best for their project and client. If DALI is the system of choice or a Bluetooth solution, it matters not to the liquid crystal lens and in either case, the lens can be controlled to achieve the desired effect.

Dynamic Beam Shaping

Experience at Light + Building and Lightfair International lead us to believe that lighting designers need no help in seeing the benefits of Dynamic Beam Shaping or imagining where it might be used. The immediate practicality in hospitality settings, museums, and retail establishments is fairly straightforward. Though OEMs and the control software will determine the beam size range, the possible settings are virtually limitless within that range. No longer are designers limited by six standard lamp distributions or the fixed aperture of appliances. It's as if a new power-tool has been invented for designers; one that allows them to easily work around variances in design, construction or changes in the size of an object. The rewards are time, money and the illuminated effect.

Luminaire manufacturers too may benefit directly as Dynamic Beam Shaping provides a path to SKU reduction, initially by requiring fewer reflector options in a product line.

It may be that solving some of today's less obvious illumination problems are what turn lighting designers into illumination superheroes. Because it's so difficult to achieve the right beam shape or change it when needed, it's not uncommon to see poor illumination effects that can now be easily addressed.

Conclusions

Lighting designers will immediately recognize the problem in the image below taken at the entrance of Harry Potter World in London. Though the beams are misplaced and not the right size, visitors can recognize and accept the images because they're immediately identifiable. Though it shouldn't be acceptable in this case, in a museum setting, it would be tragic. If Dynamic Beam Shaping had been implemented at Harry

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Potter World, the illumination scheme could, in a brief moment, be brought up to standard.

Artifacts in the light can also be resolved in many cases. Unfortunately, not all reflectors provide absolutely 'clean' light. In many cases, the use of a liquid crystal lens can smooth a beam and remove artifacts providing an immediate and valuable improvement to the luminaire.

LensVector, a pioneer in liquid crystal lens technology, is working on a lens roadmap that would allow for dynamic generation of rectilinear beams from round symmetric sources, and vice versa with linear sources. The promise of even greater, more precise beam shaping and control for all light fittings will go a long way toward fulfilling the promise of solid-state lighting as a technology that allows designers to do more with light than ever before.

References

[1] Yeh, P. and C. Gu, *Optics of liquid crystal displays.*, Vol. 67. 2010: John Wiley & Sons.

[2] Wu, S.-T. and D.-K. Yang, *Reflective liquid crystal displays.*, 2001: Wiley.

[3] de Gennes, P.-G. and J. Prost, *The physics of liquid crystals (international series of monographs on physics).*, Oxford University Press, USA, 1995. 2: p. 4.

[4] Blinov, L.M. and V.G. Chigrinov, *Electrooptic effects in liquid crystal materials.*, 2012: Springer Science & Business Media.

[5] Galstian, T.V., *mart mini-cameras.*, 2013: CRC Press.

[6] `www.lensvector.com`.

[7] Galstian, T., et al., *Optical camera with liquid crystal autofocus lens.*, Opt Express, 2017. 25(24): p. 29945-29964.

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Human Centric Lighting

142 Human Centric Lighting – Quo Vadis?
by DI Johannes Weninger, Bartenbach GmbH

148 Lighting and Emergency Department Clinician Wellness and Performance Improvement
by Octavio L. Perez, Ph.D (NOMINEE: LED professional Best Scientific Paper Award 2018), Icahn School of Medicine at Mount Sinai, Department of Population Health Science and Policy

164 A Design for Tunable LED Lighting that Reduces the Incidence of Myopia
by Dr. Stephen Mason, Sustainable Eye Health Pty

176 Implications for Human-Centric Lighting Design in Tropical Nursing Homes: A Pilot Study
by Dr. Szu-Cheng Chien (NOMINEE: LED professional Best Scientific Paper Award 2018), Singapore Institute of Technology

186 Full Spectrum LEDs and Indoor Daylight Support for Health and Wellbeing
by Octavio L. Perez, Ph.D, Icahn School of Medicine at Mount Sinai, Department of Population Health Science and Policy

Human Centric Lighting – Quo Vadis?

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Abstract

Lighting technology goes through a time of groundbreaking changes these days. The extensive application of the compact digital light source LED facilitates the generation of dynamic lighting scenarios with varying intensities, spectra and luminous intensity distributions and the implementation of new lighting designs for personal visual, biological and emotional needs. Integrating sensor-technologies and implementing complex lighting control strategies will further support the transformation of current lighting systems into adaptive lighting solutions that instantaneously react to environmental alterations and individual desires. To start a sustainable transformation process, the lighting industry has to seize the emerging opportunities, connect to information and communication technologies more closely and rethink future lighting concepts. There is a lot at stake, especially for the European lighting industry! In the following the authors present their positions based on own long-standing experiences in light impact research and lighting design.

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Introduction

The term human-centric lighting (HCL) was implemented in 2013 as part of a market study. It is a term that still has an unclear definition of its lighting concepts.Nevertheless, it aims at achieving a profound paradigm shift in lighting, which after a technologically dominant phase, now increasingly defines the user needs as a central element of its developments. This process requires a significant redefinition of requirements of future lighting technologies.

Today, lighting products are designed for general visual needs and are not able to fulfill the diversity of individual needs. Future lighting systems must be configurable to the needs of single end users and thus have to provide easy-to-use interfaces to allow effortless adjustments of lighting control parameters to personal preferences and varying demands in different everyday situations. The acceptance rates of these lighting systems will be high as this will let the end user directly experience his own individuality.

Such product designs, which are tailored to individual needs, are not new to the lighting industry. For instance, switching lights on and off at any time can be understood as a rudimentary implementation of user needs. With dimmable room lights, visual preferences of individuals were focused at even a more extended level. Both, switching and dimming, instantaneously satisfies the needs of users and thus are highly accepted. These acceptance rates can hardly be reached with automatically controlled lighting systems.

The flaws of automation

Today, automated systems play a fundamental role for human-centric lighting. With the help of lighting control strategies, which automatically change the light intensity and light color depending on the time of day, healthy light dynamics can basically be implemented. But these lighting systems thwart the user-centricity of traditional user-controlled lighting systems by disregarding personal needs and preferences.

As a consequence, the need for justification of these automated lighting systems is increased as the end user is deprived of controlling rights which are now assigned to the light expert, who defines the not-adjustable lighting control strategy.

This shift of control from the end user to the light expert raises doubts as to whether automated lighting systems maintain user centered requirements in human-centric lighting because single user parameters are not utilized to define the lighting control curves.

In contrast, lighting control strategies refer to the general circadian rhythmicity in humans which is influenced by the 24-hour light/dark rhythm. Thus, it is assumed, that changing indoor light intensities and color temperatures according to a standard day, will support circadian entrainment by light and improve human health. Although research has clearly shown, that individuals endogenously differ in the period length of their circadian systems, up to now, only non-individualized, general lighting control curves are implemented in HCL solutions. This contradicts the basic idea of user-centered systems by ignoring the individuality of different users.

Two further aspects have to be considered: light stimuli for generating non-visual effects differ significantly between individuals and end-users show a strong idiosyncratic light control behavior.

The non-standardizable light stimulus for individuals

There is strong evidence that bright light acutely increases alertness, working memory and attention performance, and alters nocturnal melatonin and early morning cortisol levels [1]. In addition, light shifts the phase and changes the amplitude of circadian parameters [2]. These non-visual light effects can hardly be separated from visual information processes.

Furthermore, it is well documented, that past light exposure of the subject, circadian phase of the subject and spatial position of the subject when exposed to relevant light stimuli, play a crucial role in generating non-visual light effects.

Past light exposure of the individual

Individual light exposure of the past hours and days has a significant impact on regulating the sensitivity of the circadian system to light [3]. It is known, that regular light-dark changes over periods of 24 hours have a stabilizing effect on circadian rhythms [4] and protect against improper light stimuli (e.g., low light levels during the day and excessive light exposure at night).

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Individually timed light exposure

Light exposure differently affects mood, cognition and behavior depending on the circadian phase of the individual [5][6]. Accordingly, timing of light exposure, especially with regard to the sleeping time, must be considered on an individual level.

The direct and indirect light input to individuals at different spatial positions

The spectral irradiance, measured at eye level, constitutes the light stimulus for generating non-visual light effects [7]. Light entering the eyes is basically composed of direct light of the luminaires as well as of indirect light, which is reflected by room surfaces. Furthermore, different spatial positions dramatically change the direct and indirect light input to humans. Thus, reflection properties of room surfaces, the emitted light intensity and light spectrum of the light sources and the position of the individual together play a crucial role in reaching certain spectral irradiances at eye level.

Taking these three parameters into account, light stimuli to achieve non-visual light effects prove to be highly variable between different subjects. Thus, it is essential to collect user-related information (e.g., light exposure history, sleep time, spatial position) and integrate this information into the light control strategy. However, as current HCL solutions are based on general pre-defined lighting control strategies, individual non-visual light needs are considerably ignored, and it can be assumed, that current HCL solution work sub-optimally.

The revolting subject — idiosyncratic light control behavior

In order to operate automatic lighting systems with maximum benefit, it is necessary to minimize user interventions. However, studies have shown that a subject's comfort is negatively affected by a lack of control of environmental parameters [8]. Furthermore, the possibility of adjusting lighting to preferred levels greatly improves both, user satisfaction and system acceptance [9][10][11][12]. Therefore, operating fully automatic lighting systems run the risk of reducing user satisfaction.

In contrast, automatically controlled lighting systems which allow user interactions to a certain extent can be established. Because user interventions are typically based on actual needs, user behavior jeopardize the achievement of long-term (non-visual) light effects [13][14][15].

Thus, automatically controlled lighting systems, which lack information on user needs and preferences, are highly likely to encounter manual adjustment of pre-defined light settings. These adjustments often do not allow lighting systems to operate as intended and designed to [8].

In fact, the desire for individualization, alignment with personal preferences and possibility to control the lighting system is so high that users prefer personally controlled poorer lighting conditions over automatically controlled better lighting conditions [16].

This user behavior is confirmed by a three-year research project of Bartenbach (psylicht), in which the general psychiatric ward and the gerontopsychiatric ward of a Tyrolean hospital were equipped with state-of-the-art automated lighting solutions with user intervention options. Over a period of 24 hours, light intensities and color temperatures were changed automatically in all areas (patient rooms, bathrooms, corridors, staff rooms and recreational areas). In an iterative process the automatic changes in light settings were optimally adapted to working processes and social rhythms (e.g., sleeping and eating times and medical treatments of the patients) of the ward.

During the day, staff and patients were exposed to high brightness levels (up to 1000 lux at the eyes) under neutral white light (4000 K). In the evening and at night, bedrooms and bathrooms of patients were illuminated with reduced light intensities ($<$ 50 lux) and the wards were lit with warm white light (2200 K). In addition, room lighting could be dimmed at any time and predefined lighting scenes (e.g., for television, eating) could be activated in recreational areas.

To measure user interventions with the lighting system as disruptive factors to generate non-visual light effects, all states of the lighting system (intensity and color temperature) as well as all user interventions, separated for each room area, were continuously recorded over a period of 18 months. Analyzing the data gave remarkable insights into the systematic individual lighting adjustment behavior.

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For example, during the last hours of night shift work, where sleep pressure is high [17], the likelihood of changing light settings manually increased significantly (see Figure 1). Although, increasing light levels may counteract decreasing nighttime alertness levels [18], this light intervention has potentially negative effects on nocturnal melatonin levels, which indicates a disruption of the circadian system and may impair human health in the long term [19]. Although by decreasing light intensities and minimizing blue light components in ambient nighttime lighting detrimental light effects on circadian rhythms of night shift workers can be reduced [20], which was intended to be reached by the lighting designer, the instantaneous satisfaction of personal needs of end-users (i.e., improving nighttime alertness level by increased morning light) was observed.

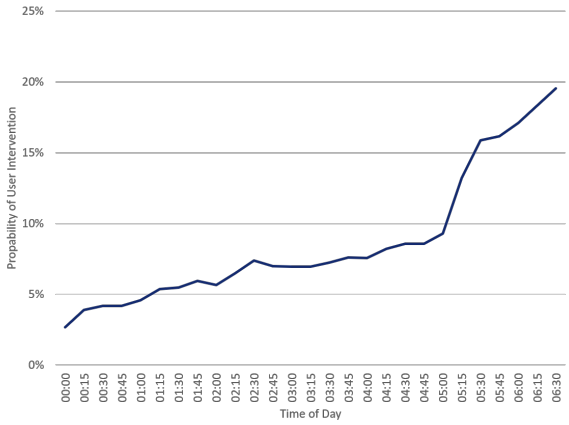

Figure 1: Daytime-specific probability of user interventions during night shift in the staff room.

These experiences, gathered within a research project, establish user satisfaction and the end user's desire to control lighting settings as a core element of future lighting control strategies. Systems that implement automatized 24-hour dynamics, based on pre-defined light settings, face a high probability to ignore basic needs of the user, which may cause manual interventions that significantly limit effective circadian lighting.

In order to prevent such a user behavior, increase acceptance rates, and maximize the efficacy of the lighting system, it is necessary to integrate situational personal preferences into lighting control concepts. Further, data about personally adjusted light settings in the past provides input for currently used light control strategies, which leads to a sound balance between preferred and circadian effective light settings.

The urge for personalization

The integration of individual parameters into lighting control strategies exceed the capabilities of current automatic lighting systems. To create personalized lighting scenarios, providing information collected at user level to the system is a necessity. Although today's HCL solutions are not ready for this information input, the implementation of connected lighting system lay the cornerstone for enabling direct communication between the lighting system, the environment and the user [21].

Thus, the implementation of personalized lighting system requires a fundamental and far-reaching change of thinking about future lighting control strategies. Rule-based control strategies, which are currently mainly implemented, are not able to meet the complexity of upcoming requirements of individual users. The use of model-based lighting control strategies [22], which are supported by artificial intelligence [23], may overcome these core limitations and establish lighting systems that are fully centered on the end-user and thus only pre-defined by lighting designers.

However, the implementation of fully user-centered lighting strategies in the long term requires that decision-making is handed over from the end user to a form of intelligence integrated into the lighting systems. Execution of this handover is extremely complex and algorithms for personalization are currently unavailable or barely applicable [13]. Personalized systems are therefore currently neither technologically nor conceptually available in the lighting industry.

Only when IP-to-the-end-node (luminaire) as well as standardized protocols for data exchange are delivered [24], fully personalized lighting control strategies without or with minimal manual intervention of end users are made possible. Finally, we expect that the development of such lighting systems will lead to a sustainable change of business models in the lighting industry.

This assumption is corroborated by an end user survey carried out by Bartenbach in the course of the research project Repro-light. A total of 1096 end users in the application fields "office" and "industry" filled out a questionnaire to rate satisfaction levels with current workplace lighting systems and to specify core features of personalized lighting solutions.

One question within this survey especially focused on the desire for personalized lighting ("If you could have a workplace lighting system, that adapts to your personal needs, would you want it?"). Analysis of the ratings clearly showed that people like the idea of a personalized lighting system (Figure 2).

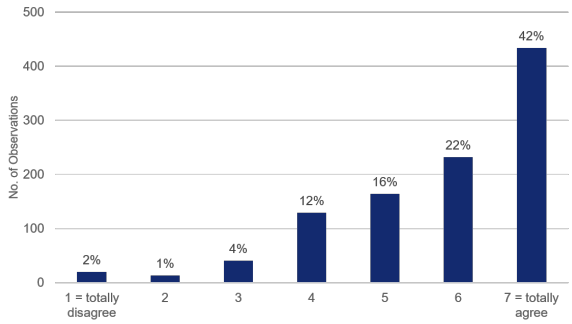

Figure 2: "If you could have a workplace lighting system, that adapts to your personal needs, would you want it?".

Thus, personalized systems potentially do not only have a long-lasting positive impact on the viability of non-visual lighting effects, but they also point to potentially higher levels of acceptance among end-users. These can be particularly appreciated by end users with increased visual demands, as they are more open to new lighting ideas and technologies due to their higher expectations regarding their workplace lighting [25].

Conclusions

The integration of user-related information in lighting control strategies is proving indispensable to implement the concept of human-centric lighting. However, current HCL solutions are primarily realized as automations and handled as technical solutions for dynamically changing light intensities and color temperatures. The technological restrictions of these automated control concepts do not make it possible to consider user information sufficiently and are thus not able to differentiate user individualities. As a result, it has become apparent that the ability of current solutions to generate non-visual light effects may be severely limited as the variability and individuality of light needs of end users are ignored.

Further, the different ideas of system requirements of light experts and end users may have a detrimental effect on system efficiency, as the predefinition of fixed light curves for automation does not coincide with personal preferences or individual user requirements. This divergence may cause needs-driven user interventions which counteract planned system behaviors and thus significantly limit effective circadian lighting. It can currently be assumed that such interventions can be minimized by appropriately handling individual differences of users in lighting control solutions.

Thus, personalized lighting can not only contribute to higher acceptance rates and user satisfaction, but also maximize non-visual light effects. However, such systems are not yet available on the market and basic technological developments are still to be researched. According to the authors, especially the definition of open, interoperable protocols should be considered important, as they not only facilitate data exchange and interoperability but also enable complex model-based control strategies.

In general, however, the basic idea of human-centric lighting is consistently proving to be correct and important, and thus remains unchanged. However, in order to no longer be subject to the conceptual and technical limitations of automated systems, the idea of HCL should be used to define requirements of technical implementations and the end user must be regarded technologically as an individual with personal qualities and opinions. Only then will it be possible to establish the user as a central element of control systems.

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References

[1] Vandewalle, G., Maquet, P., Dijk, DJ. (2009). Light as a modulator of cognitive brain function. Trends Cogn Sci. 13(10): 429–38.

[2] Khalsa, SB., Jewett, ME., Cajochen, C., Czeisler, CA. (2003). A phase response curve to single bright light pulses in human subjects. J Physiol. 549(Pt 3): 945–52.

[3] Chang, AM., Scheer, FA., Czeisler, CA. (2011). The human circadian system adapts to prior history. J Physiol. 589(Pt 5): 1095–102.

[4] Münch, M., Nowozin, C., Regente, J., Bes, F., De Zeeuw, J., Hädel, S., Wahnschaffe, A., Kunz, D. (2016). Blue-enriched morning light as a countermeasure to light at the wrong time: effects on cognition, sleepiness, sleep, and circadian phase. Neuropsychobiology 74(4): 207–218.

[5] Fisk, AS., Tam, SK., Brown, LA., Vyazovskiy, VV., Bannermann, DM., Peirson, SN. (2018). Light and Cognition: Roles for circadian rhythms, sleep, and arousal. Front Neurol 9: 1–18.

[6] Chang, AM., Santhi, N., St Hilaire, M., Gronfier, C., Bradstreet, DS., Duffy, JF., Lockley, SW., Kronauer, RE., Czeisler, CA. (2012). Human responses to bright light of different durations. J Physiol 590(13) 3103–12.

[7] Lucas, RJ., Peirson, SN., Berson DM., Brown, TM., . . . , Brainard GC. (2014). Measuring and using light in the melanopsin age. Trends Neurosci. 37(1): 1–9.

[8] Nagy, Z., Yong, F. Y., Schlueter, A. (2016). Occupant centered lighting control: a user study on balancing comfort, acceptance, and energy consumption. Energy and Buildings, 126, 310–322.

[9] Fotios, S., Logadóttir, Á., Cheal, C., Christoffersen, J. (2012). Using adjustment to define preferred illuminances: do the results have any value?. Light & Engineering, 20(2), 46–55.

[10] Despenic, M., Chraibi, S., Lashina, T., Rosemann, A. (2017). Lighting preference profiles of users in an open office environment. Building and Environment, 116, 89–107.

[11] Gilani, S., O'Brien, W. (2017). Modelling and simulation of lighting use patterns in office spaces. Building Simulation, San Francisco, CA.

[12] Escuyer, S., Fontoynont, M. (2001). Lighting controls: a field study of office workers' reactions. Transactions of the Illuminating Engineering Society, 33(2), 77–94.

[13] Fabi, V., Andersen, R. K., Corgnati, S. (2016). Accounting for the uncertainty related to building occupants with regards to visual comfort: A literature survey on drivers and models. Buildings, 6(1), 5.

[14] Boyce, P. R., Veitch, J. A., Newsham, G. R., Jones, C. C., Heerwagen, J., Myer, M., Hunter, C. M. (2006). Occupant use of switching and dimming controls in offices. Lighting Research & Technology, 38(4), 358–376.

[15] Lindelöf, D., Morel, N. (2006). A field investigation of the intermediate light switching by users. Energy and Buildings, 38(7), 790–801.

[16] O'Brien, W., Gunay, H. B. (2014). The contextual factors contributing to occupants' adaptive comfort behaviors in offices—A review and proposed modeling framework. Building and Environment, 77, 77–87.

[17] Booker, LA., Magee, M., Rajaratnam, SM., Sletten, TL., Howard, ME. (2018). Individual vulnerability to insomnia, excessive sleepiness and shift work disorder amongst healthcare shift workers. A systematic review. Sleep Med Rev., available online 27 March, 2018.

[18] Leppämäki, S., Partonen, T., Piiroinen, P., Haukka, J., Lönngvist, J. (2003). Timed bright-light exposure and complaints related to shift work among women. Scand J Work Environ Health 29(1): 22–26.

[19] Khan, S., Duan, P. Yao, L., Hou, H. (2018). Shiftwork-mediated disruptions of circadian rhythms and sleep homeostasis cause serious health problems. Int J Genomics, available online 21 Jan, 2018.

[20] Canazei, M., Pohl, W., Bliem, HR., Weiss, EM. (2016). Acute effects of different light spectra on simulated night-shift work without circadian alignment. Chronobiol Int. 34(3): 303–317.

[21] Sabourin, N. T. (2017). The effects of connected lighting on lighting controls and design.

[22] Mittal, S., Frayman, F. (1989, August). Towards a Generic Model of Configuraton Tasks. In IJCAI (Vol. 89, pp. 1395–1401).

[23] Tiihonen, J., Felfernig, A. (2017). An introduction to personalization and mass customization. Journal of Intelligent Information Systems, 49(1), 1–7.

[24] Van de Werff, T., Van Essen, H., Eggen, B. (2017). The Impact of the Internet of Lighting on the Office Lighting Value Network. Journal of Industrial Information Integration.

[25] Repro-light, D2.2: Requirements Specification, 2018

Lighting and Emergency Department Clinician Wellness and Performance Improvement

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Abstract

This multidisciplinary study is focused on the potentially beneficial 'non-visual' effects of lighting in the clinical environment, to improve clinician wellness and performance, and advance patient safety.

The hypothesis of this study was that clinician wellness and performance in the execution of clinical procedures at the emergency department (ED) could be improved through controlled, indirect, 'blue-regulated', full visible spectrum, tunable, solid state, 'white' lighting, compared to prevalent fluorescent lighting conditions.

To conduct our inquiry, we performed a randomized AB/BA crossover experimental study with ten (10) ED clinicians that executed clinical procedures, under two lighting conditions, in a realistic ED clinical setting. The experiments took place at the Emergency Department Simulation Teaching and Research Center (ED-STAR) at Mount Sinai Hospital in New York City, NY, USA, with a high fidelity human patient simulator.

The main observed outcomes of this study were: a significant reduction in clinician sleepiness perception (Karolinska Sleepiness Scale, 'KSS', −15.94%, $p = 0.022$), a significant reduction in workload perception (NASA-TLX, −21.87%, $p = 0.009$), a reduction in clinical procedures execution time (−21.04%), and a reduction in the occurrence of medical error. The experimental condition (78 000 K) was also preferred by the clinicians compared to the prevalent fluorescent lighting (4000 K), favoring the translatability from the simulation setting to the clinical environment.

We concluded that controlled lighting environments may contribute to improve clinician wellness and performance, reduce medical error, and improve patient safety. Therefore, lighting should be considered a critical factor in the design and operation of health care facilities, far beyond energy savings.

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Introduction

Short wavelength ('blue') light is known to mediate 'non-visual' effects of light in humans [81][16]. These effects, that go beyond the pure 'visual' function, can affect human wellness and performance, as it has been reported in previous scientific and technological research in laboratory, office, education, clinical and aero-space setups [54][47][29][60][80][4][5][6][83][44][17][45][11]. Lighting has been recognized in the fields of human factors, ergonomics, and systems engineering, as an environmental factor that can affect clinician wellness and performance, and the occurrence of medical error [12]. The aim and novelty of this research is to study the potentially beneficial 'non-visual' effects of lighting in the clinical environment to advance patient safety.

The hypothesis of this study was that clinician wellness and performance in the execution of clinical procedures at the emergency department (ED) can be improved through controlled, indirect, 'blue-regulated', full visible spectrum, tunable, solid state, 'white' lighting, compared to prevalent fluorescent lighting conditions.

To conduct our inquiry, we performed a randomized AB/BA (2×2) crossover experimental lighting study with ED clinicians that executed clinical procedures, in a realistic ED clinical setting, under two lighting conditions. We used the existing fluorescent lighting as control condition. To provide the appropriate experimental lighting condition, we developed a novel multichannel solid state lighting (SSL) system for precise control and assessment of the light spectrum, with specific emphasis in the short wavelength spectral area.

The results of this study suggest that it is possible that indirect, 'blue-enriched', full visible spectrum, tunable, solid state, 'white' lighting, can contribute to reduce clinician sleepiness and workload perceptions, might reduce clinical procedures execution time, and might reduce the occurrence of medical error (compared to prevalent fluorescent lighting conditions).

Background

Health care is a critical burden for modern societies, and patient safety has become a main concern in the last decades [48]. The study of the (internal) environment of care is emerging and has not been properly addressed, even if research in human factors and ergonomics points it out as a critical factor [12][13][14]. In addition, lighting, as a key factor of the environment (more specifically, of the 'exposome' [86], has not been paid enough attention except for the considerations of 'adequate *lighting levels*' for the visual task and for visual performance [13]. Improving the environment of care can have a positive impact in the quality of care and therefore in patient safety [68][42]. Other studies propose that enhancing clinician wellness might contribute to this goal [84][69]. And this is also a goal of our research, to see if through controlled lighting interventions clinician performance and clinician wellness can be improved with the final objective of having a safer delivery of care, and improvement in patient safety.

The recent adoption and development of simulation centers as part of the medical training and research provides a very appropriate setting to conduct research without the risk of harm to patients and with a high level of translatability to the real clinical setting [34][32]. For these reasons, we have conducted our research at the ED simulation center, to provide a realistic reproduction of the clinical environment.

We know that the human 'visual' system has, at least, a dual function, the 'visual' and the 'non-visual' [50][70][23]. Besides the known pure visual effects (mainly visual task and aesthetics), and the non-visual or non-image-forming (NIF) effects of light and lighting on circadian rhythms that can affect, entrain and regulate sleep patterns, disorders and disturbances (such as shift work and jet-lag) [35], research is developing in the fields of effects on human mood, cognition, performance and wellness and wellbeing [82][18].

Although there has been extensive research and development of lighting for health care delivery, mostly for the patient [80][4][5][6][83][44][17][45][11], there is no prior interventional research that specifically addresses the NIF effects of the lighting environment in the ED clinician performance and wellness in relationship with patient safety, what represents one of the main contributions of this study.

The field of research on NIF effects of light and lighting is emerging, and has several limitations that will need further research. Appropriate research in the NIF effects on lighting has only been possible since the recent discovery in 2002

of the ipRGC [39][7], the photoreceptors that mainly mediate these effects, and their presumed 'action spectra' (related to the photopigment melanopsin [8][78], also recently discovered in the late nineties by Ignacio Provencio, Ph.D [63][64][65], a reason why some researchers call the ipRGC Ignacio-Provencio-RGC). While the precise underlying neural pathways and systems and associated 'pharmacodynamics' remain unclear and will need further research from multidisciplinary approaches (such as architecture, design, engineering, physics, medicine, biology, cognitive sciences and psychology), it is known that these ipRGC photoreceptors innervate into different areas of the brain far beyond the well-known visual pathways [24].

There is a general lack of methodology in lighting research, particularly in NIF. Replication and reproducibility are basic pillars in the scientific method that must be addressed in this field. Uniformity is needed in lighting studies to allow repetition and replication and conduct proper meta-analysis [66]. Methodology becomes essential for lighting studies in the field of NIF effects. The following are proposed factors that have to be carefully considered [66][53], as subjects' psycho-physiology plays a major role: participant's chronotype (morningness/eveningness); sleep schedule of the participants during previous days, circadian time of day (CT) for the participant (time since wake-up) and other stimuli influence such as caffeine intake (in the form of coffee or other caffeinated beverages and/or supplements), Indoor Environmental Quality (IEQ), with factors such as room temperature, relative humidity and carbon dioxide (CO_2) and noise; appropriate method of light measurement, preferably based on spectral power distribution (SPD). Control conditions are also critical for the estimation of the effects beyond the classical 'statistical significance' research drivers. Using darkness [71] or unrealistic environments as controls is not ethical. These are factors that need to be properly considered in future studies. We have seen the same lack of rigorous methodology in the review of most of the studies referenced related to the effects of light and lighting in the health care environment.

One of the main limitations in current research is the paradigm, and prevailing mindset, of photometry and colorimetry in the lighting community. Light and lighting are mainly measured, and understood, in terms of illuminance (unit lux) and color appearance (correlated color temperature, 'CCT', unit Kelvin) [27]. The 'action spectra' of the ipRGC, characterized now in relationship to melatonin suppression [8][78], a point that is beginning to be questioned [67][87], is totally different from the action spectra of the classical visual photoreceptors that are the foundation for photometry and colorimetry. New metrics, such as the melanopic function (and the associated melanopic lux), or the 'melanopic equivalent daylight (D65) illuminance' to be introduced in late 2018 by CIE JTC-09, have been proposed for the measurement of light at the eye/cornea level in laboratory studies [53], but there is no common standard for measuring the field of view (FOV) and the whole lighting environment, particularly with spectral resolution (SPD). Future advancement in this field will require proper assessment of the directionality and of the whole lighting environment to better characterize the dynamic stimuli for the different space stakeholders 'competing demands', such as patient vs. caregiver in the patient room or the emergency department, and the surgeon vs. anesthesiologists vs. nurses in the operation room.

Technology availability by lighting researchers has constituted an additional limitation. Most of the previous studies in real or realistic environments have been done by non-experts in lighting with commercial light sources and fixtures designed for the visual-task function and performance. Little attention has been paid to these factors in lighting design improvement, limiting interventions (control vs. experimental setting) to lamp substitution or fixture retrofitting. Solid state lighting, and particularly LED (light emitting diode) facilitates a radical change in this limitation, particularly the 'full spectrum tunable' (not the inappropriate 'white-tunable') systems that will allow targeting specific SPDs.

Due to this current limitation, and to our experience in the development and commissioning of lighting systems, we decided to set up in our research environment an innovative lighting system that provided enough flexibility for our research at an affordable budget. We describe this in more detail in the methods section.

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Research Questions, Hypothesis and Objective

Research Questions

The main research question of this study was: "to know if there is a difference in clinician wellness and performance during the execution of clinical procedures at the ED Simulation Center due to the lighting environment". Performance was measured in qualitative terms (medical evaluation), and in differences in execution time, together with subjective workload and sleepiness/alertness metrics for wellness evaluation. Medical error occurrence was also surveilled.

We were on an exploratory research path and this was a screening experiment. Therefore we were not interested at this stage in knowing the optimum spectrum or the most efficacious system. If we obtained satisfactory proof of concept findings, as it happened, this matter would open other research oriented to optimization of our research question, to estimate the best control variables (factors) and to get the optimum values for them. There are two additional research questions of interest: 1) "What is the effect of 'blue-enriched' indirect lighting in lighting quality perception?", and 2) "'Blue-enriched' lighting, associated with high CCT, has generally not been liked by previous study participants. Is our lighting environment, diffused lighting, going to be accepted by our participants?". These secondary questions are critical for the translatability of the results into the real clinical environment.

Hypothesis

The research hypothesis was: "the clinician wellness and performance outcomes will be significantly improved with the indirect, 'blue-enriched', full visible spectrum, solid state, 'white' lighting (experimental treatment condition) compared to the existing fluorescent lighting (control treatment condition).'

Based on our previous experience and in the literature research, already disccussed in the backgrounds section, we presume that 'blue-enriched' lighting can be adequate to be part of our research. And we also know that this particular region of the spectrum can be difficult for our visual system if not delivered properly. That is why we chose to research with an indirect delivery of the lighting conditions, with no direct exposure of the light sources to the participants. This also minimizes the controversial 'Blue Light Hazard' (BLH) risks [62].

Objective

The objective of the study was "to investigate the efficiency of indirect, 'blue-enriched', full visible spectrum, solid state, 'white' lighting in clinician wellness and performance, and patient safety, during the execution of a single-clinician clinical procedure, 'chest- tube', in the Emergency Department simulation lab." The first procedure was taken as a 'warm-up'.

Methods

We will discuss here the experimental design (AB/BA crossover, within subjects), the research tools (with a special emphasis in the lighting intervention and the lighting system), the population, and the statistical model for the study (that has to be properly defined before running the tests)[1].

The whole experimental flowchart is shown in figure1. There are three main processes, the experimental design and IRB (Internal Review Board), the experimental runs, and the data analysis, though we will not explore them here in detail.

Experimental Design

We conceived, designed and conducted 'proof of concept' experimental research. We had two lighting conditions (control and experimental), and we randomized our sample of participants (real ED clinicians) into two groups, sequences AB and BA. Group AB performed the test (two sequenced clinical procedures 'airway' + 'chest-tube') first under control lighting condition (fluorescent) and then under experimental ('blue-enriched' LED), and BA group did the reverse order/sequence. Participants took a 'wash-out' period of at least one full week (7 days) between the treatments/conditions (tests). The process flow is shown graphically in Figure 2.

[1] "*To call in the statistician after the experiment is done may be no more than asking him to perform a post-mortem examination: he may be able to say what the experiment died of.*" Ronald Fisher (1890–1962)

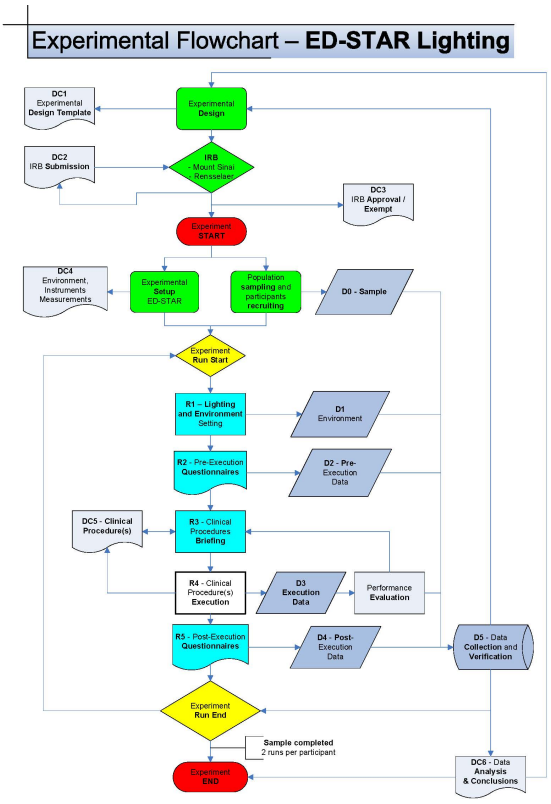

Figure 1: ED-STAR Experimental Methods Flowchart.

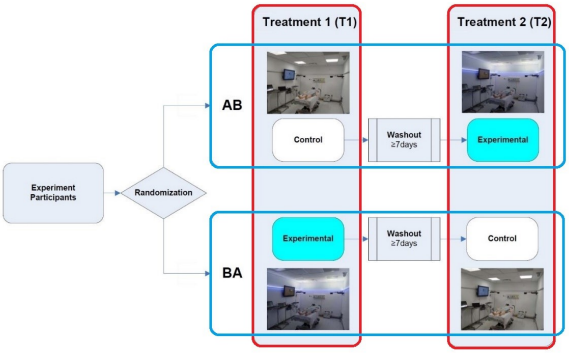

Figure 2: Experimental design AB/BA crossover flow.

Research Tools

For the experimental lighting condition (treatment), we developed our own instruments and systems and used as the control the existing lighting system (fluorescents). This system will be described in the next subsection.

For the experimental instruments, we used validated surveys and questionnaires: the 'Karolinska Sleepiness Scale' (KSS) for subjective assessment of sleepiness/alertness [2][46][75][41], the 'NASA-TLX' ('TLX': 'Task Load Index) for subjective workload perception [37][38][49], a modified version of the 'ASHRAE IEQ survey' [88] for subjective assessment of the environment, and a 'Lighting Perception Survey' for the subjective perception of lighting, based on the initial work by Prof. Peter R. Boyce [30], that we updated to gather additional information. We used custom ED-STAR tables for clinician performance and time evaluation.

Lighting Intervention and Lighting System

At the time of the study, there were no commercial options to provide illumination levels of a room such as the ED-STAR 'simlab' for the purposes of the experimental framework proposed here, with full control over the visible spectrum (SPD). The only existing systems that were able to provide room level 'color tunability' (different from SPD control) were the Philips 'Healwell' and the Telelumen 'Penta', that provide color (perceptual) tunability, but not detailed spectral tunability. This, as discussed, is particularly relevant on the 'blue' region of the visible spectrum (short wavelengths) that are critical mediators of the 'non-visual' effects of light. Besides the SPD limitation, both systems are based on direct ceiling light emission, contrary to the IES-RP-29 recommended practice for healthcare facilities, which prioritizes indirect lighting for spaces that have interactions with patients. For these reasons, we proceeded to build a custom system at the 'simlab' which provided full SPD controllability with an indirect lighting strategy.

Figure 3 shows the 'simlab' room as it was in May 2015 prior to proceeding with Mount Sinai facilities to retrofit the room for this research. The room was originally illuminated by four recessed ceiling troffers (2'×2' fixtures). The walls were painted in an unspecified 'off-white' with the head wall painted (arbitrarily) in a 'beige' color.

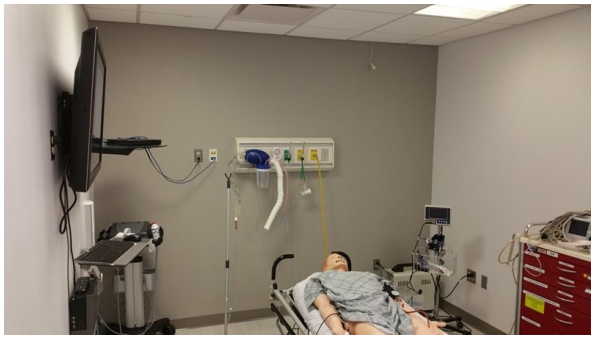

Figure 3: ED-STAR room before the lighting intervention.

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Figure 4: ED-STAR room after the lighting intervention.

The first intervention was to paint all the walls of the room with a 'high reflective white' (Light Reflectance Value, LRV = 94%) paint to make the room an integral part of the lighting system. We also painted two ceiling tiles with the same paint, as they were going to be working as primary reflectors of the light engines that were providing full spectrum tunability. This also provided maximum spectral fidelity of the reflected light and minimum absorption by the surfaces (a factor that should be considered also for energy efficiency).

Figure 4 shows the final configuration of the system as conceived for the experimental condition with two main sources of light (besides the existing fluorescent that was used as control condition, and turned off in the experimental condition):

- Two full spectrum light engines in the front side of the room shining upwards at above average eye level to prevent direct eye exposure to the LED light sources
- A perimeter lighting profile to provide indirect lighting and uniformity perception across the room

Both sources of light had different control systems and were commanded through the same communication and control bus (through standard DMX512 protocol). A schematic of the system is depicted in Figure 5 where we can see the two lighting sources and their associated control systems, the DMX communication bus, system controller (lighting controller), the networking interface and the control software interfaces (android/iPhone 'apps' and PC software). The reason to use the wireless network layer instead of a cabled layer for the control was to provide full electrical isolation between the user interface and the lighting system (lighting as a medical device safety).

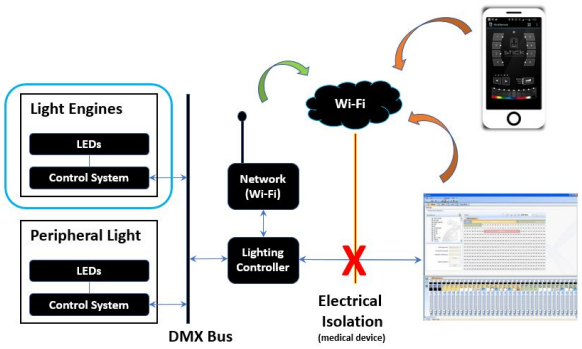

Figure 5: Lighting System Schematic.

The **light quality** of the two lighting conditions is shown in figures 6 and 7. The measurements were taken with a calibrated Konica-Minolta CL-500A spectrophotometer. We can see that even if the experimental condition was with a high 'blue' content, and at the limit of the black body line (BBL) to be considered "white" (78 000 K), the color fidelity was higher than the conventional fluorescents. Of particular interest for the health care environment is the R9 parameter associated with 'red' perception (skin/blood). We did not calculate the 'Cyanosis Observation Index' (COI) from Australian regulations (AS/NZS 1680.2.5), as it does not affect USA and EU countries.

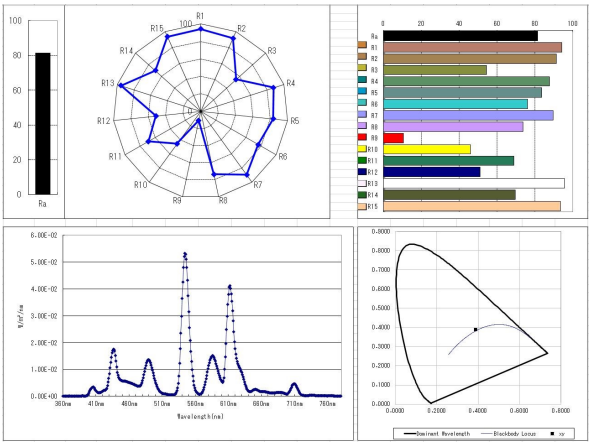

Figure 6: Control Condition Light Quality.

Lighting System Commissioning in the Clinical Health care Environment. Once the system was built and installed, we proceeded with the commissioning (programming). Our target for the experiment was to have the same illuminance levels (lux) at the task under both lighting conditions (880 lux), as we can see in figure 8.

The fluorescent lighting had no control, besides the classical on/off, and we manually adjusted the

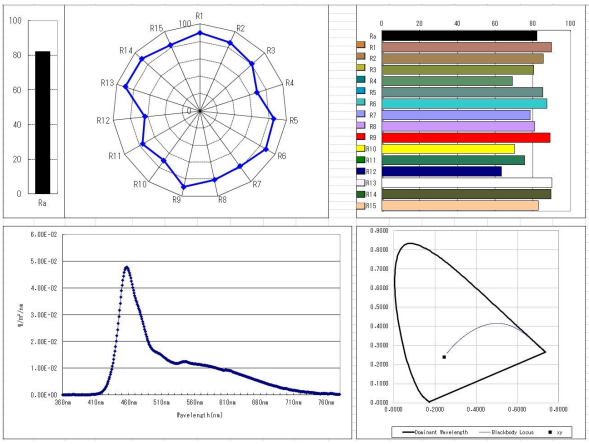

Figure 7: Experimental Conditions Light Quality.

new experimental lighting system until it achieved the desired experimental condition, with the constraint of providing the same illuminance as the fluorescent system (at the task). This setting was saved as a preset in the lighting system controller (Nicolaudie Stick KE1 with network adapter). The ED-STAR staff was able to setup the room with the push of a button ('mode 5') in the smartphone 'app'. This was demonstrated to be a very robust procedure with no possible mistakes. The staff was very confident about this way of operation.

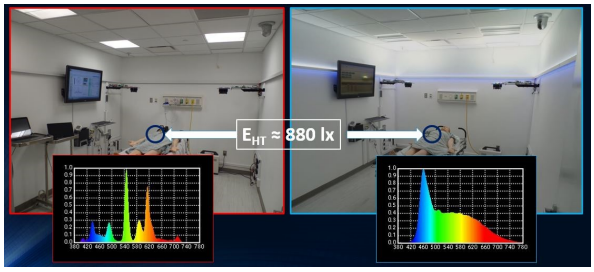

Figure 8: equilux Lighting Conditions: control (left) and experimental (right).

Subjects. Study Population

The research study enrolled emergency department clinicians following the Institutional Review Board (IRB) approved protocol. The study was performed in the Emergency Department Simulation Teaching and Research Center (ED-STAR), a teaching simulation center at Mount Sinai Hospital in NYC, NY, USA. Our experimental setup is a permanent installation that will enable further research with the goal of rapid translatability into the real ED clinical environment.

Statistical Model: AB/BA crossover

An AB/BA crossover study is defined as one experiment or clinical trial in which there is an interest in determining differences between two treatments that are given in alternate order to two groups of participants. One group, AB, received first treatment A and then treatment B. The other group, BA, received the treatments in reverse sequence (first B and then A) [73][74][57][51]. Each participant on a crossover acts as his/her own control eliminating the between-participant's variability, needing less observations than the parallel design to get the same precision in estimation. A crossover study is therefore more efficient than a parallel group study.

The statistical model for the AB/BA crossover is summarized in figures 9 and 10 [73]. Figure 9 shows the four cells, with the means and expectations for each cell. The variables in this figure are:

- General level parameter: μ
- Treatment contrast (treatment effect): $\tau = \tau A - \tau B$
- Period effects: $\pi 1$ and $\pi 2$

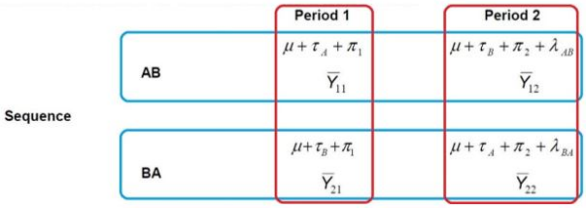

Figure 9: Cell means and expectations for a cross over design.

Figure 10, shows the estimation of the parameters of interest ('treatment effect' and 'carry-over') based on the four cell means $\bar{Y}11$, $\bar{Y}12$, $\bar{Y}21$, $\bar{Y}22$ (where $\bar{Y}11$ is the mean of the first group/sequence, AB, in period 1, and so on).

Name	Definition	Expectation
CROS	$[(\bar{Y}_{11} - \bar{Y}_{12}) + (\bar{Y}_{22} - \bar{Y}_{21})]/2$	$(\tau_A - \tau_B) - (\lambda_{AB} - \lambda_{BA})/2 = \tau - \lambda/2$
SEQ	$(\bar{Y}_{11} + \bar{Y}_{12}) - (\bar{Y}_{22} + \bar{Y}_{21})$	$(\lambda_{AB} - \lambda_{BA}) = \lambda$
PAR	$\bar{Y}_{11} - \bar{Y}_{21}$	$(\tau_A - \tau_B) = \tau$

Figure 10: Estimation of parameters of interest from the cell means for a cross over design.

Continuous and discrete variables

In a crossover study, we have to differentiate carefully between continuous and discrete variables.

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Discrete Variables

For the discrete variables, we did a study based on contingency tables.

Continuous Variables

For the continuous variables, we evaluated first the **treatment effect** ('effect size') provided by the crossover analysis and the 95% confidence interval. The 'effect size' provides the magnitude of the treatment effect and the sign indicates the direction of the effect (higher or lower under experimental compared to control).

Then we proceed with the **null hypothesis statistically significance testing**: - Null hypothesis H0: mean difference is zero (no statistical significant difference) - Alternate hypothesis H1: we have two different alternate hypothesis

1. mean difference is less than zero (one sided) for:
    - KSS ('Karolinska Sleepiness Scale')
    - NASA-TLX ('Task Load Index')
    - Clinical procedures 'execution time'
2. mean difference is greater than zero (one sided) for:
    - Clinical procedures 'performance'

The reason for the two different criteria for the alternate hypothesis is due to the expected hypothesized effects:

- For KSS (sleepiness/alertness) we expect a lower sleepiness (higher alertness) with the experimental treatment. Same with NASA-TXL where a lower score will indicate a lower perceived workload. Lower 'execution time' (in seconds) for the clinical procedures is also expected under the experimental condition
- For clinical procedures 'performance' evaluation we hypothesize to have higher scores under experimental conditions compared to control.

We calculate the 'p-value' that will be communicated as exact value [79][36][85]. With the treatment effects information (magnitude and direction) and the statistical significance, we will discuss the results and relevance in the next section.

Example of Communication of Crossover Results for Continuous Outcomes

As there is no standardized way for communicating crossover study results, besides the tables, we will summarize the results in the following format:

In the crossover analysis of outcome yyy, measured zzz, (n = ww) we obtained the following results:

- Treatment effect = x.xx95% CI [x.xx, x.xx].
- Mean C (Control) was higher/lower (MC = x.x, SDC = x.xx) than Mean E (Experimental) (ME = x.x, SDE = x.xx), by (xx%), t(DF) = x.xx, p = .xxx

Experimental Runs, Results, and Data Analysis

Experimental Conditions

All participants had a minimum 'wash-out' period of at least seven (7) days between experimental runs in order to preclude 'carry-over' effects. 'Carry-over' can be associated with the learning process (cognitive/psychological) more than the physiological 'carry-over' of typical drug crossover studies. Participants were not on night-shifts for at least two days prior to either of the two treatments. The ideal situation would have been to avoid all night-shifts, but this could not be accomplished with active ED clinicians, and it is also closer to the real conditions of the ED environments where experimental results will be translated. We also arranged the timing of the experiment in terms of days of the week and time frames within the day (noon-4pm). All the experiments were conducted during weekdays, excepting Mondays to avoid the potential 'post-weekend' effect, also known as 'Monday effect' [10].

Sample/Participants

Our sample was composed of ten active clinicians (n = 10) from the ED department at Mount Sinai Hospital in NYC (even if ten subjects could be seen initially as a low number, the fact that they were actual clinicians in a realistic clinical environment adds robustness to our study, that is exploratory). All of the participants were volunteers and did not receive any compensation for participation. They were very helpful in

accommodating their busy, and sometimes unpredictable, working schedule to the experimental research agenda, with the strict limitation of the two night shifts.

Characterization of the sample:

- size: ten (n = 10) participants (equivalent to 20 on a double arm experiment)
- experimental runs: twenty (20), two per participant, following the AB/BA crossover design
- age: average 35.10 years (SD = 4.95, min = 28, max = 44)
- gender: seven males and three females
- experience level: five residents (3th and 4th year) and five faculty members
- all participants were healthy, and none declared having diabetic conditions, nor color vision problems
- one participant had light-colored eyes

There was no participant drop-out.

Experimental Results and Data Analysis

The data collection and initial processing of the data was done in 'MS Excel' and the statistical analysis was performed using 'Minitab v17'. As the experimental design was AB/BA crossover, we have used the crossover statistical analysis methodology for the inferential statistics analysis of the data. The crossover design has the unique characteristic of having each participant as its own control, reducing the variability between participants and the sample size required compared to double-arm designs. Besides the conventional inferential study of 'p-values', statistical significance, that has become controversial, yet pervasive, we have also conducted a study of the 'treatments effects' to discuss practical significance [56][21][40][55][79][77][22][61][36][85].

Experimental data for KSS and NASA-TLX is shown in different figures and tables in this section: KSS differences within test in Table 1 and Figure 11, the KSS equivalence test in Figure 14; NASA-TLX differences within test in Table 2 and Figure 12, the NASA-TLX equivalence test in Figure 15; crossover data analysis results summary for KSS and NASA-TLX in Figure 13; the summary of inferential statistics in Table 3. Detailed data for clinical performance execution time and evaluation, and for the surveys is not presented here.

Table 1: Within participants' experimental runs KSS differences within test.

	Group	Karolinska Sleepiness Scale (KSS)								
Study	Seq	Control		ΔKSS-C	Experimental		ΔKSS-E	KSS - C-E	Period	
#	AB/BA	Pre	Post	C	Pre	Post	E	C-E	T1	T2
01	**AB**	2	4	2	5	4	-1	3	2	-1
03	AB	4	4	0	5	4	-1	1	0	-1
05	AB	5	4	-1	4	3	-1	0	-1	-1
06	AB	7	3	-4	7	4	-3	-1	-4	-3
07	AB	3	3	0	4	4	0	0	0	0
09	AB	3	3	0	3	3	0	0	0	0
02	**BA**	6	6	0	3	2	-1	1	-1	0
04	BA	6	6	0	6	5	-1	1	-1	0
08	BA	6	5	-1	7	4	-3	2	-3	-1
10	BA	1	2	1	4	4	0	1	0	1
		43	40	**-3**	48	37	**-11**	**8**		
			Effect	**-6.98%**		**Effect**	**-22.92%**	**15.94%**		
			Mean	-0.3		**Mean**	-1.1	0.8	**Mean Diff**	
			SD	1.57		**SD**	1.10	1.35	**Pooled SD**	

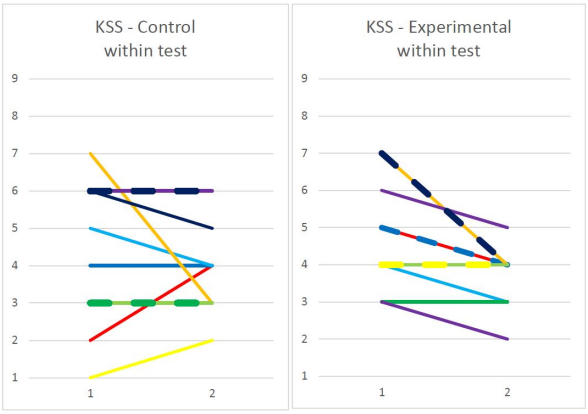

Figure 11: Within participants' experimental runs KSS differences within test (1=baseline (pre-test), 2=after procedures (post-test)): Control (left) vs. Experimental (right). Dotted lines represent more than one test with exact results: two 3–3 and two 6–6 occurrences under control (left); two 7–4, two 5–4 and two 4–4 under experimental (right).

Table 2: Within participants' experimental runs NASA-TLX differences within test (missing data for participant #02 experimental condition).

	Group	NASA-TLX Raw (TLX)				
Study	Seq	Sum of scales			Sum of scales	
#	AB/BA	C	E	C-E	TLX1	TLX2
01	AB	87	67	20	87	67
03	AB	51	47	4	51	47
05	AB	39	41	-2	39	41
06	AB	41	33	8	41	33
07	AB	73	62	11	73	62
09	AB	45	18	27	45	18
02	BA	50	*	*	*	50
04	BA	70	49	21	49	70
08	BA	30	30	0	30	30
10	BA	35	21	14	21	35
		521	368	103		
		471	**368**	**103**	**-21.87%**	(exc #02)
	Mean	52.33	40.89	11.44		
	SD	19.69	17.07	18.43	**Pooled SD**	

The observations of reduction of sleepiness (KSS) and workload (NASA-TLX), factors that may be associated with clinician wellness/stress

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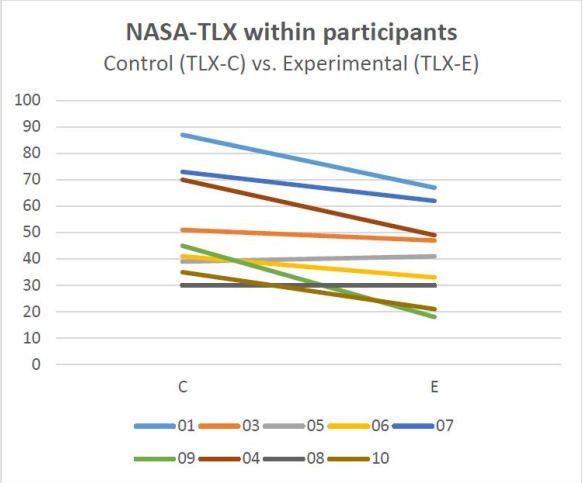

Figure 12: NASA-TLX within participants (Control vs. Experimental: TLX-C vs. TLX-E)(missing data for participant #02 experimental condition).

Crossover Data Analysis Results Summary

1. Sleepiness Perception (KSS)

In the crossover analysis of KSS, (measured in a scale 9-1), n=10, we obtained the following results:

- Treatment effect -0.875, 95% CI [-1.7174, -0.032555]
- The Mean under Control (M_C = -0.3, SD_C = 1.57) was higher than the Mean under experimental (M_E = -1.1, SD_E = 1.10), by 15.94%, DF(8), T-value=-2.3951, p-value=0.022

We observed in our sample that the experimental condition reduces the KSS (sleepiness perception) as hypothesized, in the terms described above.

2. Workload Perception (NASA-TLX)

In the crossover analysis of NASA-TLX, (measured 1-126), n=9 (1 participant's score missing), we obtained the following results:

- Treatment effect -11.5, 95% CI [-20.393, -2.6074]
- The Mean under Control (M_C = 52.33, SD_C = 19.69) was higher than the Mean under experimental (M_E = 40.89, SD_E = 17.07), by 21.87%, DF(7), T-value=-3.0579, p-value=0.009

We observed in our sample that the experimental condition reduces the NASA-TLX (workload perception) as hypothesized, in the terms described above.

Figure 13: Crossover data analysis results summary for KSS and NASA-TLX.

Equivalence Test for 2x2 Crossover Design: CD, KSS-T1, KSS-T2

Method

Treatment order for subjects in sequence AB: KSS-C, KSS-E
Treatment order for subjects in sequence BA: KSS-E, KSS-c

Descriptive Statistics

		KSS-T1		KSS-T2	
C1	N	Mean	StDev	Mean	StDev
AB	6	-0.50000	1.9748	-1.0000	1.0954
BA	4	-1.2500	1.2583	0.000000000	0.81650

Within-subject standard deviation = 0.40020

Effects

	Effect	SE	DF	T-Value	P-Value	95% CI
Carryover	0.25000	1.6809	8	0.14873	0.885	(-3.6262, 4.1262)
Treatment	**-0.87500**	0.36533	8	-2.3951	0.044	(-1.7174, -0.032555)
Period	0.37500	0.36533	8	1.0265	0.335	(-0.46744, 1.2174)

Difference: Mean(KSS-E) - Mean(KSS-C)

Difference	SE	95% Upper Bound	Upper Limit
-0.87500	0.36533	-0.19566	0

Upper bound is less than 0
Can claim Mean(KSS-Exp) < Mean(KSS-Ctrl)

Test

Null hypothesis: Mean(KSS-E) - Mean(KSS-C) ≥ 0
Alternative hypothesis: Mean(KSS-E) - Mean(KSS-C) < 0
α level: 0.05

DF	T-Value	P-Value
8	-2.3951	**0.022**

P-Value ≤ 0.05. Can claim Mean(KSS-Exp) < Mean(KSS-Ctrl)

Figure 14: KSS Equivalence Test from Minitab.

Equivalence Test for 2x2 Crossover Design: CD, TLX-T1, TLX-T2

Method

Treatment order for subjects in sequence AB: TLX Ctrl, TLX Exp
Treatment order for subjects in sequence BA: TLX Exp, TLX Ctrl

Descriptive Statistics

		TLX-T1		TLX-T2	
CD	N	Mean	StDev	Mean	StDev
AB	6	56.000	19.545	44.667	18.250
BA	3	33.333	14.295	45.000	21.794

Within-subject standard deviation = 3.76070

Effects

	Effect	SE	DF	T-Value	P-Value	95% CI
Carryover	-22.333	25.461	7	-0.87714	0.410	(-82.540, 37.873)
Treatment	**-11.500**	3.7607	7	-3.0579	0.018	(-20.393, -2.6074)
Period	0.16667	3.7607	7	0.044318	0.966	(-8.7260, 9.0593)

Difference: Mean(TLX Exp) - Mean(TLX Ctrl)

Difference	SE	95% Upper Bound	Upper Limit
-11.500	3.7607	-4.3751	0

Upper bound is less than 0. Can claim Mean(TLX Exp) < Mean(TLX Ctrl)

Test

Null hypothesis: Mean(TLX Exp)-Mean(TLX Ctrl) ≥0
Alternative hypothesis: Mean(TLX Exp)-Mean(TLX Ctrl) <0
α level: 0.05

DF	T-Value	P-Value
7	-3.0579	**0.009**

P-Value ≤ 0.05. Can claim Mean(TLX Exp) < Mean(TLX Ctrl)

Figure 15: NASA-TLX Equivalence Test from Minitab (missing data for participant #02 experimental condition).

and medical error causation in the health care environment, are of special interest in the emergency setting. In the ED environment, clinicians work under high levels of stress [19]. The potential increased ability of saving lives is a major component of the practical significance of our study.

The experimental lighting environment was positively accepted by the study participants and our indirect, 'blue-enriched', full visible spectrum, solid state, 'white' lighting (experimental condition) was evaluated in our sample as better than the existing and prevalent fluorescent lighting (control condition). There were slight differences in perception of temperature and humidity: the environment was perceived as more humid and warmer under control (fluorescent) conditions. The experimental condition was accepted by all the participants of our study, except one, and had less claims for controllability. Also, the experimental condition was evaluated as better than the control in the 'compared to other workplaces' survey. It is the first time in lighting research that 'blue-enriched' full visible daylight lighting delivery has been reported under experimentation with an equivalent CCT of ≈ 78 000 K (seventy-eight thousand Kelvin) at the task. This setting was considered better than the conventional lighting (control condition).

We observed in our sample a reduction in sleepiness (alertness? increase) in the KSS scale

Table 3: Summary of Inferential Statistics.

Summary of inferential statistic tests						
Control: Existing fluorescent (4,000K)						
Experimental: Solid State (LED) lighting system (78,000K)						
H_0 Null hypothesis: Mean(Experimental) - Mean(Control) ≥ 0						
H_1 Alternative hypothesis: Mean(Experimental) - Mean(Control) < 0						
	Values	Effect	Effect %	alpha	P-Value	Result
Karolinska Sleepiness Scale						
KSS	9-1	-0.88	**-15.94%**	**0.05**	**0.022**	**Can Reject H_0**
NASA-TLX (workload perc.)						
Sum of scales	1-21 x 6	-11.50	**-21.87%**	**0.05**	**0.009**	**Can Reject H_0**
				0.01	**0.009**	**Can Reject H_0**
Clinical Performance Execution Time	seconds					
Procedure 1 (P1): Airway		-6.17	**-21.35%**	0.05	0.252	*Cannot Reject*
Procedure 2 (P2): Chest-tube		-101.46	**-21.02%**	0.05	0.090	*Cannot Reject*
Total Execution Time (P1+P2)		-107.63	**-21.04%**	0.05	0.094	*Cannot Reject*
H_0 Null hypothesis: Mean(Experimental) - Mean(Control) ≤ 0						
H_1 Alternative hypothesis: Mean(Experimental) - Mean(Control) > 0						
Clinical Performance Evaluation						
Procedure 1 (P1): Airway						
Checklist (P1C)	1-12	0.21	**1.77%**	0.05	**0.182**	*Cannot Reject*
Psychomotor (P1P)	1-7	0.17	**1.64%**	0.05	0.239	*Cannot Reject*
Novice to Expert (P1N)	1-5	0.25	**7.32%**	0.05	**0.138**	*Cannot Reject*
Procedure 2 (P2): Chest-tube						
Checklist (P2C)	1-34	0.63	**4.04%**	0.05	**0.160**	*Cannot Reject*
Psychomotor (P2P)	1-7	-0.04	**0.00%**	0.05	0.534	*Cannot Reject*
Novice to Expert (P2N)	1-5	0.21	**5.26%**	0.05	**0.182**	*Cannot Reject*

(−15.94% observed effect with p-value = 0.022), Figure 11, and a reduction in workload perception in the NASA-TLX sum of scales (−21.87% observed effect with p-value = 0.009), Figure 12. We cannot claim a statistically significant reduction in execution times for procedure two and total execution times (−21.04% observed effect with p-value = 0.094). Also, there was no improvement seen in the clinical performance evaluation, even if we can see an observed effect improvement in our study in the scores from control to experimental lighting conditions. Finally, two medical errors occurred under control conditions and none under experimental conditions.

Discussion

We have obtained results from our experimental research that are supportive of our hypothesis about potential 'non-visual'/'non-image-forming' (NIF) beneficial effects of 'blue-enriched' full visible spectrum 'white' lighting in clinician wellness and performance, and improvement in patient safety. The observed reduction in sleepiness (increase in alertness? awakeness?) and the observed reduction in perceived workload, the effect in clinical performance, and the acceptance and preference of the experimental condition (indirect, 'blue-enriched', full visible spectrum, solid state, 'white' lighting) compared to the control condition (fluorescent lighting) are discussed here. These results may contribute to the translatability of the findings from the simulated to the actual clinical environment.

Our experimental lighting condition suggested an aggregate set of beneficial results for clinician wellness and performance that supports our research hypothesis. Using the existing fluorescent lighting as control reinforced the validity of our study, as these are ubiquitous conditions in the current health care environment.

The acceptance of the experimental lighting condition is critical for its practical feasibility. Also, our lighting conditions provided general lighting performance, while results from previous research that has been conducted in lightboxes [71] or on 'ad-hoc' laboratory setups (static subjects with fixed chin) [8] are difficult to be translated into real-world environments.

The observed reduction in sleepiness, associated with an increase in alertness (awakeness?), might initially seem inconsistent with the observed reduction in workload perception, as alertness could be erroneously associated with stress and arousal. In our study, the participants interviewed agreed that the experimental lighting provided a 'calming effect' that empowered them to better focus on the execution of the clinical procedures. This 'calming effect', which at the same time improves alertness (awakeness?) and focus, requires further research and analysis (explored in fields such as mindfulness). Another potential explanation can be found in the (controversial?) field of 'Syntonic Optometry' where the effect of 'blue' visible radiation is associated with the activation of the parasympathetic nervous system activation (PSNS), [76][52][33]. The field of pharmacodynamics [28] becomes relevant here as perhaps the same wavelength/relative SPD can create different effects depending on levels/dose (and timing).

Taking into account that we performed all of our experiments between noon and 4pm (trying to have a similar circadian time, 'CT', lapse for the participants), we presume that melatonin suppression, or reduction, was not the cause of the effect measured. Melatonin levels are high in the human body during the night and remain low during the day [43]. In the selection of our timeframe we were also careful to not target the morning peak of cortisol. Considering that our timeframe was coincident with the 'post-prandial' dip, previous research suggests that the

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orexin/hypocretin neurons that are associated with wakefulness [25][15][26][72][20] might be inhibited by higher glucose levels associated with high carbohydrate meals [9]. Monk [58] recognizes the post-meal effect, and also the carbohydrates factor, but also proposes that the decrease in performance in the early afternoon could be driven by a 12-hour circadian harmonic that could also be higher in morning-type individuals, and that is not necessarily caused by the post-meal event. Monk also proposes ('bright') light as a coping mechanism for the 'siesta' effect. To the best of our knowledge, only one previous lighting research [66] considers the orexin wakefulness mechanisms in association with lighting, beyond the effects of light in melatonin.

This is clearly an area of future research related to the study of the neurological mechanism underlying the effects of light in human psycho-physiology that would be difficult to conduct in other organisms (such as mice) due to the high level cognitive functions associated with the research, and the fact that mice are nocturnal creatures. Techniques such as fMRI (functional Magnetic Resonance Imaging) have been proposed in the field of neuroscience, even if the statistical methods in neuroimaging have been put recently into question [31]. Other neuro-physiological metrics, such as heart rate variability (HRV), eye tracking (pupillary response), electroencephalography (EEG), and skin conductivity, look very promising to evaluate sympathetic and parasympathetic nervous system activation and should be explored in future studies.

Conclusions and Future Work

We have seen in this exploratory research that controlled lighting environment can be beneficial in the health care environment, particularly in the execution of ED clinical procedures. These environments can improve clinician wellness and performance, and advance patient safety.

This can have a huge impact in the field of health care ergonomics and particularly in the emergent burden of clinician burnout, a topic that has become a priority to the National Academy of Medicine (NAM) [59].

Future work is to expand the scope of our study to advance patient safety in related clinical situations, such as: clinician cognitive recovery from medical error, hand-offs, and improvement of teamwork conditions. These are known clinical scenarios where prevalence of adverse events has been observed, that might be prevented and precluded through environmental interventions such as controlled lighting. Dynamic lighting, temporal effects, ethics, human variability factors, and the interoperability between lighting systems and human objective psycho-physiological variables will be considered.

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References

[1] AHRQ. 2008. “Healthcare Expenses for Adults with Chronic Conditions, 2005.” Statistical Brief #203. Rockville, MD: Agency for Healthcare Research and Quality.

[2] Akerstedt, T, and Mats Gillberg. 1990. “Subjective and Objective Sleepiness in the Active Individual.” International Journal of Neuroscience 52 (1–2): 29–37.

[3] Anjali, Joseph. 2006. “The Impact of Light on Outcomes in Healthcare Settings.” Issue Paper #2. Concord, CA: The Center for Health Design.

[4] Beauchemain, K. M., and Peter Hays. 1996. “Sunny Hospital Rooms Expedite Recovery from Severe and Refractory Depressions.” Journal of Affective Disorders 40 (1–2): 49.

[5] Beauchemin, Kathleen M., and Peter Hays. 1998. “Dying in the Dark: Sunshine, Gender and Outcomes in Myocardial Infarction.” Journal of the Royal Society of Medicine 91 (7): 352–354.

[6] Benedetti, Francesco, Cristina Colombo, Barbara Barbini, Euridice Campori, and Enrico Smeraldi. 2001. “Morning Sunlight Reduces Length of Hospitalization in Bipolar Depression.” Journal of Affective Disorders 62 (3): 221–223.

[7] Berson, David M., Felice A. Dunn, and Motoharu Takao. 2002. “Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock.” Science 295 (5557): 1070–1073.

[8] Brainard, George C., John P. Hanifin, Jeffrey M. Greeson, Brenda Byrne, Gena Glickman, Edward Gerner, and Mark D. Rollag. 2001. “Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor.” The Journal of Neuroscience 21 (16): 6405–6412.

[9] Burdakov, Denis, Lise T. Jensen, Haris Alexopoulos, Rhiannan H. Williams, Ian M. Fearon, Ita O’Kelly, Oleg Gerasimenko, Lars Fugger, and Alexei Verkhratsky. 2006. “Tandem-Pore K+ Channels Mediate Inhibition of Orexin Neurons by Glucose.” Neuron 50 (5): 711–22.

[10] Butler, Richard J., Nathan Kleinman, and Harold H. Gardner. 2014. “I Don’t like Mondays: Explaining Monday Work Injury Claims.” Industrial & Labor Relations Review 67 (3 suppl): 762–783.

[11] Canellas, Francesca, Luisa Mestre, Miriam Belber, Guillem Frontera, Mary Angeles Rey, and Ruben Rial. 2015. “Increased Daylight Availability Reduces Length of Hospitalisation in Depressive Patients.” European Archives of Psychiatry and Clinical Neuroscience 266 (3): 277–80.

[12] Carayon, Pascale. 2012. “Emerging Role of Human Factors and Ergonomics in Healthcare Delivery–A New Field of Application and Influence for the IEA.” Work 41 (Supplement 1): 5037–5040.

[13] Carayon, Pascale, Anping Xie, and Sarah Kianfar. 2013. “Human Factors and Ergonomics.” In Making Health Care Safer II: An Updated Critical Analysis of the Evidence for Patient Safety Practices. Evidence Reports/Technology Assessments 211. Rockville, MD: Agency for Healthcare Research and Quality.

[14] Carayon, Pascale, Tosha B. Wetterneck, A. Joy Rivera-Rodriguez, Ann Schoofs Hundt, Peter Hoonakker, Richard Holden, and Ayse P. Gurses. 2014. “Human Factors Systems Approach to Healthcare Quality and Patient Safety.” Applied Ergonomics 45 (1): 14–25.

[15] Carter, Matthew E., Luis de Lecea, and Antoine Adamantidis. 2013. “Functional Wiring of Hypocretin and LC-NE Neurons: Implications for Arousal.” Frontiers in Behavioral Neuroscience 7: 1–7.

[16] Chellappa, Sarah Laxhmi, Roland Steiner, Peter Blattner, Peter Oelhafen, Thomas Götz, and Christian Cajochen. 2011. “Non-Visual Effects of Light on Melatonin, Alertness and Cognitive Performance: Can Blue-Enriched Light Keep Us Alert?” Edited by Michael H. Herzog. PLoS ONE 6 (1): e16429.

[17] Choi, Joon-Ho, Liliana O. Beltran, and Hway-Suh Kim. 2012. “Impacts of Indoor Daylight Environments on Patient Average Length of Stay (ALOS) in a Healthcare Facility.” Building and Environment 50 (April): 65–75.

[18] Choi, Kyungah, and Hyeon-Jeong Suk. 2016. “Dynamic Lighting System for the Learning Environment: Performance of Elementary Students.” Optics Express 24 (10): A907.

[19] Cheng, Yi Han, Gregory D Roach, and Renee MA Petrilli. 2014. “Current and Future Directions in Clinical Fatigue Management: An Update for Emergency Medicine Practitioners: Clinical Fatigue Management Strategies.” Emergency Medicine Australasia 26 (6): 640–44.

[20] Chieffi, Sergio, Marco Carotenuto, Vincenzo Monda, Anna Valenzano, Ines Villano, Francesco Precenzano, Domenico Tafuri, et al. 2017. “Orexin System: The Key for a Healthy Life.” Frontiers in Physiology 8 (May).

[21] Coe, Robert. 2002. “It’s the Effect Size, Stupid: What Effect Size Is and Why It Is Important.” In British Educational Research Association Annual Conference. Exeter, England.

[22] Cumming, Geoff. 2013. Understanding the New Statistics: Effect Sizes, Confidence Intervals, and Meta-Analysis. Multivariate Applications Series. New York, NY, United States of America: Routledge.

[23] Dai, Jiapei, Jan Van Der Vliet, Dick F. Swaab, Ruud M. Buijs, and others. 1998. “Human Retinohypothalamic Tract as Revealed by in Vitro Postmortem Tracing.” The Journal of Comparative Neurology 397 (3): 357–370.

[24] Daneault, V., M. Dumont, é. Massé, G. Vandewalle, and J. Carrier. 2016. “Light-Sensitive Brain Pathways and Aging.” Journal of Physiological Anthropology 35 (1): 12.

[25] de Lecea, Luis, Matthew E. Carter, and Antoine Adamantidis. 2012. “Shining Light on Wakefulness and Arousal.” Biological Psychiatry 71 (12): 1046–52.

[26] de Lecea, Luis, and Ramón Huerta. 2014. “Hypocretin (Orexin) Regulation of Sleep-to-Wake Transitions.” Frontiers in Pharmacology 5 (16): 1–7.

[27] DiLaura, David L. 2005. “Light’s Measure: A History of Industrial Photometry to 1909.” Leukos 1 (3): 75–149.

[28] DiPiro, Joseph T., William J. Spruill, William E. Wade, Robert A. Blouin, and Jane M. Pruemer. 2010. Concepts in Clinical Pharmacokinetics. Fifth Edition. Bethesda, MD: American Society of Health-System Pharmacists, Inc.

[29] US Department of Energy. 2013. “Implementing Spectrally Enhanced Lighting.” DOE/EE-1048. Building Technologies Office. US Department of Energy.

[30] Eklund, Neil H., and Peter R. Boyce. 1996. “The Development of a Reliable, Valid, and Simple Office Lighting Survey.” Journal of the Illuminating Engineering Society 25 (2): 25–40.

[31] Eklund, Anders, Thomas E. Nichols, and Hans Knutsson. 2016. “Cluster Failure: Why FMRI Inferences for Spatial Extent Have Inflated False-Positive Rates.” Proceedings of the National Academy of Sciences 113 (28): 7900–7905.

[32] Gardner, Aimee K., Dmitry Nepomnayshy, Craig Reickert, Denise W. Gee, Ryan Brydges, James R. Korndorffer, Daniel J. Scott, and Ajit K. Sachdeva. 2016. “The Value Proposition of Simulation.” Surgery 160 (3): 546–51.

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[33] Gottlieb, Ray, and Larry Wallace. 2001. “Syntonic Phototherapy.” Journal of Behavioral Optometry 12/2001 (2): 31–38.

[34] Gray, Whitney Austin, Karen S. Kesten, Stephen Hurst, and Laura Anderko. 2012. “Using Clinical Simulation Centers to Test Design Interventions: A Pilot Study of Lighting and Color Modifications.” HERD: Health Environments Research & Design Journal 5 (3): 46–65.

[35] Diepen, Hester C. van, Russell G. Foster, and Johanna H. Meijer. 2015. “A Colourful Clock.” PLoS Biology 13 (5): e1002160.

[36] Greenland, Sander, Stephen J. Senn, Kenneth J. Rothman, John B. Carlin, Charles Poole, Steven N. Goodman, and Douglas G. Altman. 2016. “Statistical Tests, P Values, Confidence Intervals, and Power: A Guide to Misinterpretations.” European Journal of Epidemiology 31 (4): 337–50.

[37] Hart, Sandra G., and Lowell E. Staveland. 1988. “Development of NASA-TLX Task Load Index — Results of Empirical and Theoretical Research.” In Human Mental Workload. North Holland Press.

[38] Hart, Sandra G. 2006. “NASA-Task Load Index (NASA-TLX); 20 Years Later.” In Proceedings of the Human Factors and Engineering Society (HFES) 50th Annual Meeting, 50:904–908. San Francisco, California: Sage Publications.

[39] Hattar, S., Hsi-Wen Liao, Motoharu Takao, David M. Berson, and King-Wai Yau. 2002. “Melanopsin-Containing Retinal Ganglion Cells: Architecture, Projections, and Intrinsic Photosensitivity.” Science 295 (5557): 1065–70.

[40] Hedges, Larry V. 2008. “What Are Effect Sizes and Why Do We Need Them?” Child Development Perspectives 2 (3): 167–171.

[41] Hommes, Vanja, and Marina C. Giménez. 2015. “A Revision of Existing Karolinska Sleepiness Scale Responses to Light: A Melanopic Perspective.” Chronobiology International 32 (6): 750–56.

[42] Iyendo, Timothy Onosahwo, Patrick Chukwuemeke Uwajeh, and Ezennia Stephen Ikenna. 2016. “The Therapeutic Impacts of Environmental Design Interventions on Wellness in Clinical Settings: A Narrative Review.” Complementary Therapies in Clinical Practice 24 (August): 174–88.

[43] Jennum, Poul, Erik Lykke Mortensen, Steen Gammeltoft, Katja Linda Waller, Martin Lauritzen, Merete Osler, Birgitte Fagerlund, and Kirsten Avlund. 2016. “Melatonin and Cortisol Profiles in Late Midlife and Their Association with Age-Related Changes in Cognition.” Nature and Science of Sleep 8 (January): 47–53.

[44] Joarder, A., A. Price, and M. Mourshed. 2009. “Systematic Study of the Therapeutic Impact of Daylight Associated with Clinical Recovery.” In Improving Healthcare Infrastructures through Innovation, 25–31. Brighton, UK: HaCIRIC.

[45] Joarder, A., and A. Price. 2013. “Impact of Daylight Illumination on Reducing Patient Length of Stay in Hospital after Coronary Artery Bypass Graft Surgery.” Lighting Research and Technology 45 (4): 435–49.

[46] Kaida, Kosuke, Masaya Takahashi, Torbjörn Åkerstedt, Akinori Nakata, Yasumasa Otsuka, Takashi Haratani, and Kenji Fukasawa. 2006. “Validation of the Karolinska Sleepiness Scale against Performance and EEG Variables.” Clinical Neurophysiology 117 (7): 1574–81.

[47] Keis, Oliver, Hannah Helbig, Judith Streb, and Katrin Hille. 2014. “Influence of Blue-Enriched Classroom Lighting on Students’ Cognitive Performance.” Trends in Neuroscience and Education 3–4: 86–92.

[48] Kohn, Linda T., Janet M. Corrigan, and Molla S. Donaldson. 2000. To Err Is Human: Building a Safer Health System. Washington, D.C.: National Academies Press.

[49] Levin, Scott, Daniel J. France, Robin Hemphill, Ian Jones, Kong Y. Chen, Dorsey Rickard, Renee Makowski, and Dominik Aronsky. 2006. “Tracking Workload in the Emergency Department.” Human Factors: The Journal of the Human Factors and Ergonomics Society 48 (3): 526–539.

[50] Lewy AJ, Wehr TA, Goodwin FK, Newsome DA, Markey SP. 1980. “Light Suppresses Melatonin Secretion in Humans.” Science 210 (4475): 1267–69.

[51] Li, Tianjing, Tsung Yu, Barbara S. Hawkins, and Kay Dickersin. 2015. “Design, Analysis, and Reporting of Crossover Trials for Inclusion in a Meta-Analysis.” Edited by Lamberto Manzoli. PLoS ONE 10 (8): e0133023. https://doi.org/10.1371/journal.pone.0133023.

[52] Liberman, Jacob. 1986. “The Effect of Syntonic (Colored Light) Stimulation on Certain Visual and Cognitive Functions.” Journal of Optometric Vision Development 27 (June): 4–14.

[53] Lucas, Robert J., Stuart N. Peirson, David M. Berson, Timothy M. Brown, Howard M. Cooper, Charles A. Czeisler, Mariana G. Figueiro, et al. 2014. “Measuring and Using Light in the Melanopsin Age.” Trends in Neurosciences 37 (1): 1–9.

[54] Mayron, Lewis W., John Ott, Ricks Nations, and Ellen L. Mayron. 1974. “Light, Radiation, and Academic Behavior.” Intervention in School and Clinic 10 (1): 33–47.

[55] McGough, James J., and Stephen V. Faraone. 2009. “Estimating the Size of Treatment Effects: Moving beyond p Values.” Psychiatry (Edgemont) 6 (10): 21–29.

[56] McGraw, Kenneth O., and S. P. Wong. 1992. “A Common Language Effect Size Statistic.” Psychological Bulletin 111 (2): 361–65.

[57] Mills, Edward J, An-Wen Chan, Ping Wu, Andy Vail, Gordon H Guyatt, and Douglas G Altman. 2009. “Design, Analysis, and Presentation of Crossover Trials.” Trials 10 (27): 1–6.

[58] Monk, Timothy H. 2005. “The Post-Lunch Dip in Performance.” Clinics in Sports Medicine 24 (2): e15–23.

[59] National Academy of Medicine. 2017. “Action Collaborative on Clinician Well-Being and Resilience.” https://nam.edu/initiatives/clinician-resilience-and-well-being/ (last accessed 2018-06-01)

[60] NASA. 2015. “NASA Technology Roadmaps — TA6: Human Health, Life Support, and Habitation Systems.” 2015 TA 6. NASA.

[61] Nuzzo, Regina, and others. 2014. “Statistical Errors.” Nature 506 (7487): 150–152.

[62] O’Hagan, J B, M Khazova, and L L A Price. 2016. “Low-Energy Light Bulbs, Computers, Tablets and the Blue Light Hazard.” Eye 30 (2): 230–33.

[63] Provencio, Ignacio, Guisen Jiang, Willem J. De Grip, William Par Hayes, and Mark D. Rollag. 1998. “Melanopsin: An Opsin in Melanophores, Brain, and Eye.” Proceedings of the National Academy of Sciences, Neurobiology, 95 (1): 340–45.

[64] Provencio, Ignacio, Ignacio R. Rodriguez, Guisen Jiang, William Pär Hayes, Ernesto F. Moreira, and Mark D. Rollag. 2000. “A Novel Human Opsin in the Inner Retina.” The Journal of Neuroscience 20 (2): 600–605.

[65] Provencio, Ignacio. 2011. “The Hidden Organ in Our Eyes.” Scientific American 304 (5): 54–59.
[66] Rautkylä, Emilia. 2011. “Research Methods and Neurophysiological Mechanisms behind the Alerting Effects of Daytime Light Exposure.” Doctoral Dissertation, Helsinki, Finland: Aalto University.
[67] Rahman, Shadab A., Melissa A. St Hilaire, Claude Gronfier, Anne-Marie Chang, Nayantara Santhi, Charles A. Czeisler, Elizabeth B. Klerman, and Steven W. Lockley. 2018. “Functional Decoupling of Melatonin Suppression and Circadian Phase Resetting in Humans: Decoupled Melatonin Suppression and Phase Resetting.” The Journal of Physiology 596 (11): 2147–57.
[68] Reiling, John, Hughes, Ronda G., and Mike R. Murphy. 2008. “Chapter 28. The Impact of Facility Design on Patient Safety.” In Patient Safety and Quality: An Evidence-Based Handbook for Nurses. Rockville, MD: Agency for Healthcare Research and Quality.
[69] RCGP. 2015. “Patient Safety Implications of General Practice Workload.” London, England: Royal College of General Practitioners.
[70] Sadun, Alfredo A., Judith D. Schaechter, and Loise E.H. Smith. 1984. “A Retinohypothalamic Pathway in Man: Light Mediation of Circadian Rhythms.” Brain Research 302: 371–77.
[71] Sahin, Levent, and Mariana G. Figueiro. 2013. “Alerting Effects of Short-Wavelength (Blue) and Long-Wavelength (Red) Lights in the Afternoon.” Physiology & Behavior 116–117: 1–7.
[72] Schwartz, Michael D., and Thomas S. Kilduff. 2015. “The Neurobiology of Sleep and Wakefulness.” Psychiatric Clinics of North America 38 (4): 615–44.
[73] Senn, Stephen. 1996. “The AB/BA Cross-over: How to Perform the Two-Stage Analysis If You Can’t Be Persuaded That You Shouldn’t.” In Liber Amicorum Roel van Strik, 93–100. Rotterdam: Erasmus University.
[74] Senn, Stephen. 2002. Cross-over Trials in Clinical Research. Second Edition. Statistics in Practice. Chichester, England: John Wiley & Sons, Ltd.
[75] Shahid, Azmeh, Kate Wilkinson, Shai Marcu, and Colin M. Shapiro. 2011. “Karolinska Sleepiness Scale (KSS).” In STOP, THAT and One Hundred Other Sleep Scales, edited by Azmeh Shahid, Kate Wilkinson, Shai Marcu, and Colin M Shapiro, 209–10. New York, NY: Springer New York.
[76] Spitler, H.R. 1941. The Syntonic Principle — Its Relation to Health and Ocular Problems. Eaton, OH: College of Syntonic Optometry.
[77] Sullivan, Gail M., and Richard Feinn. 2012. “Using Effect Size—or Why the P Value Is Not Enough.” Journal of Graduate Medical Education 4 (3): 279–82.
[78] Thapan, Kavita, Josephine Arendt, and Debra J. Skene. 2001. “An Action Spectrum for Melatonin Suppression: Evidence for a Novel Non-Rod, Non-Cone Photoreceptor System in Humans.” The Journal of Physiology 535 (1): 261–267.
[79] Thirthalli, Jagadisha, and Ravi Philip Rajkumar. 2009. “Statistical versus Clinical Significance in Psychiatric Research—An Overview for Beginners.” Asian Journal of Psychiatry 2 (2): 74–79.
[80] Ulrich, Roger. 1984. “View through a Window May Influence Recovery.” Science 224 (4647): 224–225.
[81] Vandewalle, Gilles, Christina Schmidt, Geneviève Albouy, Virginie Sterpenich, Annabelle Darsaud, Géraldine Rauchs, Pierre-Yves Berken, et al. 2007. “Brain Responses to Violet, Blue, and Green Monochromatic Light Exposures in Humans: Prominent Role of Blue Light and the Brainstem.” PLoS ONE 2 (11): e1247.
[82] Veitch, Jennifer A., and Shelley L. McColl. 2001. “A Critical Examination of Perceptual and Cognitive Effects Attributed to Full-Spectrum Fluorescent Lighting.” Ergonomics 44 (3): 255–79.
[83] Walch, Jeffrey M., Bruce S. Rabin, Richard Day, Jessica N. Williams, Krissy Choi, and James D. Kang. 2005. “The Effect of Sunlight on Postoperative Analgesic Medication Use: A Prospective Study of Patients Undergoing Spinal Surgery” Psychosomatic Medicine 67 (1): 156–63.
[84] Wallace, Jean E., Jane B. Lemaire, and William A. Ghali. 2009. “Physician Wellness: A Missing Quality Indicator.” The Lancet 374 (9702): 1714–1721.
[85] Wasserstein, Ronald L., and Nicole A. Lazar. 2016. “The ASA’s Statement on p-Values: Context, Process, and Purpose.” The American Statistician 70 (2): 129–33.
[86] Wild, C. P. 2005. “Complementing the Genome with an ‘Exposome’: The Outstanding Challenge of Environmental Exposure Measurement in Molecular Epidemiology.” Cancer Epidemiology Biomarkers & Prevention 14 (8): 1847–50.
[87] Zeitzer, Jamie M. 2018. “When Is a Proxy Not a Proxy? The Foibles of Studying Non-Image Forming Light: Perspectives.” The Journal of Physiology 596 (11): 2029–30.
[88] Zhao, Mingjie, Yang-Seon Kim, and Jelena Srebric. 2015. “Occupant Perceptions and a Health Outcome in Retail Stores.” Building and Environment 93 (November): 385–94.

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A Design for Tunable LED Lighting that Reduces the Incidence of Myopia

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Abstract

The role of sunlight in influencing eye-ball growth has been well established. Recent research has made the case that links myopia (short-sightedness) and inadequate exposure to the necessary levels of sunlight. Other researchers have established the wavelengths of visible light that trigger the so-called 'retinal dopamine response' instigated by the non-visual receptors, intrinsically photosensitive retinal ganglion cells (ipRGCs) as the primary zeitgeber for the circadian rhythm. Laboratory research using dopamine agonists and visual deprivation experiments in mammals supported by epidemiological evidence now suggests the retinal dopamine response plays a central role in the neural and dopamine-neuro-transmitter control of eye-growth and therefore the pathogenesis of myopia. Myopia is now regarded by WHO as a global epidemic. On average, developed and developing nations have experienced a three-fold increase in myopia over the past three decades. In South Korea and China (and most of eastern Asia), 80 percent of high school graduates and 95 percent of university graduates are myopic. Apart from the personal costs, inconvenience and disability, myopia brings elevated risk of ocular morbidity for many of these sufferers in later life (glaucoma, macular degeneration, retinal detachment and cataract) which in turn poses the risk of an onerous burden on health and welfare costs both at a personal and State level. Once thought to be due to prolonged reading and close work, it is now understood that the primary cause of myopia is reduced exposure to sunlight and its beneficial effects at the retinal level. Myopia represents a global health issue with the risk of profound visual disability for potentially millions of sufferers in coming years. This paper provides an overview of the peer reviewed academic research and background to the neuro-physiology of the visual and non-visual processes responsible for achieving emmetropia (no visual error) and how with current LED technology, the strategic application of appropriately designed human-visuo-centric tunable LED lighting can play a vital and essential role in supporting the developing eyesight of humans to minimize the incidence and progression of myopia.

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Myopia: epidemiology, aetiology and the role of light

Research published by the Brien Holden Vision Research Institute at the University of New South Wales, Australia in 2016 [1], revealed the alarming statistic that over the past thirty or so years, myopia has increased 300 percent, sometimes more, in both developed and developing nations. For some years the shared but mistaken view amongst researchers was the increased reading and computer time to which school, university students and office workers were subject was the central reason for this increased frequency of myopia on a global scale[2].

Many researchers overlooked the background exposure to ambient light experienced by the subjects of their research. They also commonly relied on questionnaires for both subjects and sometimes for children or their parents, which may not always be a true and accurate history of reading/study and time spent outdoors [3]. Often in comparing cohorts, the crucial variable of ambient light exposure was not accounted for. Indeed, parental myopia and near work were typically targeted by researchers as the most likely contributory factors which explained the variable results found in the literature. The Orinda Study remains as a seminal study of a significant cohort across various ethnic groups that contributed to the future direction of research, helping to steer research in the direction that ultimately revealed the role of light in the development of myopia[4]. It was a helpful step as it did consider ethnicity and concluded: "*Both nature and nurture play a role in the etiology of myopia, although the predominant role appears to belong to a positive parental history of myopia. This role does not appear to be through an interaction between parental myopia status and children's near work activity.*" The Orinda Study had helped to decouple the connection between a genetic effect and near work. It was not the genes that caused reading to trigger the development of myopia. Myopia could develop either with or without myopic parents in children who performed the same amount of reading and near work.

A publication in the British Journal of Medicine in June 2018 has clarified this view. Using a large DNA database of more than 67,000 subjects, combined with a questionnaire, researchers confirmed that time spent in *education* has a very positive association with myopia[5]. Mountjoy et al used Mendelian randomisation, "*a type of instrumental variable analysis that uses genetic variants associated with a risk factor (eg, education) as proxies for an environmental exposure to make causal inferences about the effect of the exposure on the outcome of interest (eg, myopia). This approach reduces bias from confounding and reverse causation, to which observational epidemiology studies are susceptible.*"

An important step was made in understanding the aetiology of myopia with the published research by Rose and Morgan in 2008 regarding the central role that sunlight played in significantly reducing the incidence of myopia in a population of Chinese school children[6]. Rose and Morgan's work showed that increased exposure to sunlight in the intervention cohort, significantly reduced the incidence of myopia when compared to the control cohort whilst allowing for other potentially confounding factors such as parental myopia and near work. The role of light as a central factor in understanding myopia began to align with the published research in the biological sciences on the retinal and central nervous system (CNS) effects that might be responsible for such an outcome. Stone in 1989 published the first research to outline the connection between the retinal dopamine response and eye growth[7].

Preservation of the circadian rhythm and the pupillery light reflex in certain eye pathologies made researchers long consider the existence of a mechanism that contributed to our circadian rhythm and pupillery light reflex quite apart from the rods and cones that provided the initial response to light within the retina so contributing to vision. In 1995 Czeisler et al. [8] published their findings on the preservation of a normal circadian rhythm in a number of subjects without light perception. This suggested a retinal system sensitive to light but not projecting to the visual cortex but to an area within the mid-brain controlling the release of melatonin, the supra-chiasmic nucleus (SCN). This was supported by clinical observations.

In advanced end-stage glaucoma damage to the optic nerve from elevated intra-ocular pressure causes destruction of all retinal ganglion cells, including the fibres projecting from the ipRGCs. Clinically this presents as optic atrophy. These patients typically experience circadian drift and their endocrinology does not respond to the ocular stimulation of bright light[9]. On the other hand, in patients suffering from Lebers Hereditary

Optic Atrophy (LHOA) the ipRGCs are preserved. Both disease states have the same end-stage outcome of poor vision and typically blindness. In their final expression, both conditions render the eyes devoid of light perception. Despite this, those suffering from LHOA tend not to experience circadian drift[10]. The clinical observations of the preservation of a normal circadian rhythm in LHOA but not in end-stage glaucoma pointed to a discrete neuro-sensory system to receive and process light that governed circadian rhythm and the pupillery response to light but not projecting to the visual cortex of the brain.

Research by Foster et al confirmed it was not the rods and cones responsible for setting the circadian clock [11] but an altogether separate system still capable of responding to light and communicating with the mid-brain for circadian control and the sustained pupillery reflex.

The so-called 'intrinsically photosensitive retinal ganglion cells' or ipRGCs were later identified by Bergsen et al[12]. Research by Provencio et al identified the presence of melanopsin, a unique retinal opsin unique to the ipRGCs (but common across nocturnal rodents as well as diurnal primates), as the photo-pigment initiating the response to light[13].

The primary source of retinal dopamine is found in the amacrine cells, their cell bodies in the inner nuclear layer of the retina that synapse directly with ipRGCs found in the inner-most ganglion cell layer of the retina [14]. The melanopsin photopigment found in ipRGCs responds maximally at 480 nm; so maximal release of retinal dopamine must be elicited by stimulating the ipRGC/amacrine cell pathway by exposing the retina to an adequate stimulus of light rich in wavelength at 480 nm. This corresponds naturally with the wavelength that triggers maximum inhibition of melatonin from the pineal gland. The ipRGC's therefore performing a dual function as the primary receptors for management of circadian entrainment and also central to the emmetropization process regulating eye growth. The ipRGC response is two-fold: firstly, a neurological and intrinsic response to light by the de-polarization of the cell by photon transduction of melanopsin that is directed to the mid brain via the optic tract to the SCN/hypothalamus. Secondly, by synaptic communication with retinal amacrine cells, the release of dopamine that influences eye growth.

Neuro-anatomy of the retinal dopamine pathway

The mammalian retina is referred to as an 'inverted retina'. Light, after entering the eye through the pupil and passing through the lens and vitreous, is normally focused on the retina at the posterior pole forming an inverted image of the object of regard. The retinal architecture is arranged with specialized light sensitive visual cells, the rods and cones, within the outer retinal layers. Light must pass through the transparent retinal layers before reaching these cells deepest within the retinal anatomy (Figure 1).

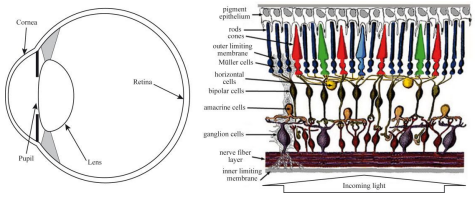

Figure 1: Anatomy of the inverted mammalian retina.

The visual pathway of rods (for night vision) and cones (for colour and day vision) progressing from the retina to the occipital cortex at the back of the brain is well defined and has been understood for many years.

Clinicians commonly diagnose lesions of the eye (e.g., glaucoma), optic nerve (e.g., side-effects from drugs/inflammation/optic neuritis) and brain lesions (e.g., stroke or tumor) by visual field analysis with a sound working knowledge of the classic pathway of the visual fibers (Figure 2).

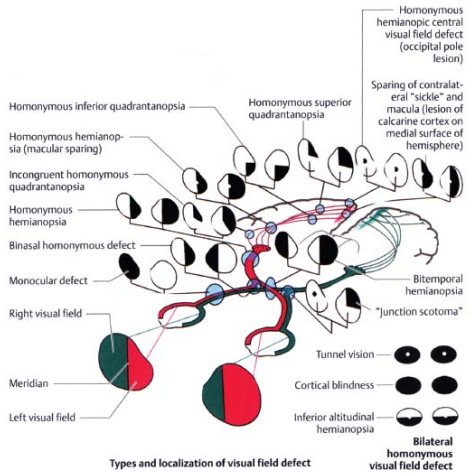

Figure 2: Visual pathway.

In recent years, these diagnoses are combined and supported with CT scan and Magnetic Resonance Imaging (MRI). However, a complete

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and comprehensive understanding of the neuro-anatomy of the *non-visual fibers* has eluded vision scientists for some time.

Bounded by the vitreous and the internal limiting membrane of the retina, is the innermost layer of the sensory retina, the retinal ganglion cell (RGC) layer. The retinal ganglion cells are responsible for receiving the signals from the rods and cones (via bipolar cells) and by virtue of their long axons traversing the sensory retina, form the optic nerve. The ipRGCs are a small subclass of the retinal ganglion cell population being less than one percent of the RGC's in primates and are anatomically found within the RGC layer. With reference to Figure 1, it can be seen that light must pass through the layer of the RGC's and ipRGCs prior to being received by rods and cones. The ipRGCs synapse with other nearby specialized retinal cells within the inner retina, amacrine cells, and it is the amacrine cells that release dopamine when triggered by the light stimulation of the ipRGCs (Figure 3).

The ipRGCs contain their unique photo-pigment melanopsin, shown to respond maximally to light stimulus at (approximately) 480 nm [15].

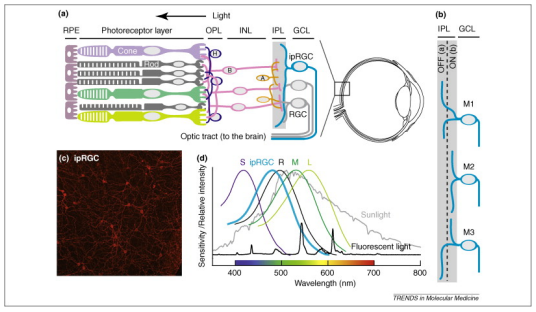

Figure 3: A diagram of ipRGC retinal architecture and spectral sensitivity.

The ipRGCs are the primary sensory elements that signal via the optic nerve and the SCN to the hypothalamus and the pineal gland influencing the release of melatonin, the pathway central to the control over circadian rhythm. Several classes of ipRGC's have been identified, namely M1 to M5 [16]. M1 ipRGC's have a strong intrinsic photo-response and project to i) the SCN for circadian control and ii) the olivary pretectal nucleus (OCN) accommodating the nucleus of the 3rd cranial nerve controlling pupillery response, these being two sub-types of M1 ipRGC's. M1 ipRGCs are therefore responsible for the sustained pupillery constriction with their fibres projecting to the nucleus of the 3rd cranial nerve (in the area of the superior colliculus) then returning anteriorly ultimately to the sphincter pupillae muscle within the iris. Retinal light stimulus by this pathway reduces the pupillery area in brighter light so autonomically limiting retinal illuminance.

Laboratory rodents are often cited in the literature: it is helpful to note that mammals share a highly comparable circadian system with light as the primary zeitgeber to triggering and entraining this natural diurnal cycle[17]. Note that nocturnal rodents possess a similar retinal structure to humans, (although typically more rod-rich when nocturnal) and light similarly stimulates the ipRGC/superior chiasmic nucleus pathway[18]. The neural response typically however in nocturnal species is that light sends them to sleep; in humans it wakes us up.

As light passes through the retina and stimulates ipRGC response particularly with light rich in blue at 480 nm, the response of ipRGC's is seen at various levels. There will be inhibition of the release of melatonin from the pituitary gland so supporting the 'wakefulness' period and there will be stimulation of amacrine cells to release dopamine. As will become relevant later, it should be noted that pharmacologically, melatonin and dopamine are antagonists. A sustained period of exposure to light and particularly blue light at 480 nm causes a sustained firing of the ipRGC/amacrine cell pathway.

The summary by Zhou [19] that reviewed the research on the mechanism behind retinal dopamine and its effect on eye growth provides a useful model of the inter-action of the dual systems of retinal dopamine receptors, respectively D1 and D2. The model proposed outlined the close inter-action between the D1 and D2 receptors that when appropriately balanced results in emmetropia (see Figure 4).

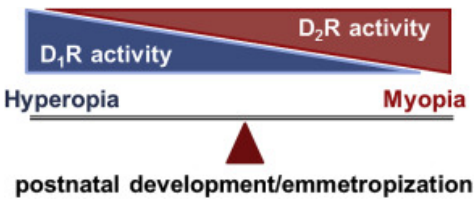

Figure 4: Zhou et al (2017) Inter-action of D1 and D2 Receptors.

Particular laboratory approaches are known to cause myopia in birds and mammals. Form deprivation myopia (FDM) for example, which is shielding the eye of a laboratory animal with an

opaque occluder; another is lens-induced-myopia (LIM), which consists of placing a spectacle mounted lens of known power before the tested eye to cause defocus of the retinal image. These techniques cause reduced retinal dopamine release in the tested eye. However, the intra-vitreal injection of dopamine agonists (e.g., apomorphine) into the tested eye, inhibits both FDM and LIM [20]. If restoring the dopamine signaling pathway with apomorphine counter-acts the dopamine inhibition effect of patching or optical defocus of the retinal image, the case for a dopaminergic pathway being central to eye-growth has effectively been made. The role of dopamine playing a key role in eye-growth has been reviewed extensively in other publications[21].

Myopia and Ambient Light

In 2015, Professor Scott Read from the Queensland University of Technology published findings on the role of ambient light exposure and its role in affecting myopic development[22]. Read showed that there was a significant difference in axial growth of the eyes in school children comparing those exposed to more lux-hours (less eye-growth) to those exposed to a lesser amount of lux-hours (more eye-growth). That is, the amount of axial elongation and myopia was significantly *more* for school children who got less lux-hours as opposed to those who received more lux-hours. Read's research entailed children wearing wrist bands that measured the amount of light exposure as well as their physical movement and exercise. His research was conclusive for the beneficial effect of more ambient light to slow and prevent myopic development. Read's results suggested exposure to higher levels of luminance were beneficial:

"*Categorized according to their objectively measured average daily light exposure and adjusting for potential con-founders (age, sex, baseline axial length, parental myopia, near-work, and physical activity), children experiencing low average daily light exposure (mean daily light exposure: 459 ± 117 lux, annual eye growth: 0.13 mm/y) exhibited significantly greater eye growth than children experiencing moderate (842 ± 109 lux, 0.060 mm/y), and high (1455 ± 317 lux, 0.065 mm/y) average daily light exposure levels (*P = 0.01*)*."

Hua et al published important findings studying school children in China, also in 2015 [23]. Hua increased the illumination in classrooms using fluorescent globes and measured the effect on the development of myopia. There were more than 300 school children across 56 classrooms from four school campuses aged between 6 and 14 years of age. Prior to intervention, the average illumination in the classrooms was $\sim$ 100 Lux at desk height. After intervention, the desk illumination was $\sim$ 500 Lux. After one year, the frequency of myopia in the control arm (no change in illumination) was 10 percent. In the intervention arm (increased illumination), the frequency of myopia was 4 percent. Increasing the available light at desk height to 500 Lux had the beneficial effect of reducing the incidence of myopia in this case by more than one half.

Tunable LEDs applied to inhibit Myopia.

In the context of i) retinal dopamine response now confirmed as subject to the ipRGC/amacrine cell pathway and influencing eye-growth ii) Read's research [22], which showed (approximately) 840–1450 average lux per day had a positive effect on reducing axial elongation of the eye and iii) the work of Hua [23] which showed increasing the available luminance at desk height of school children to 500 Lux had a positive benefit in reducing the incidence of myopia, when considered collectively, this presented as an application for the processor control of LED lighting that could provide the necessary wavelengths and luminance over time for required retinal responses to positively impact on reducing the frequency and progression of myopia.

A solution depended on providing adequate average daily lux of adequate duration with the *correct spectral distribution* to trigger the retinal dopamine response whilst also respecting the circadian rhythm.

It is important at this stage to note other work that revealed children with poor sleep quality were more susceptible to high myopia[24]. This link between the status of eye-growth and a history of sleep disruption points strongly to the link between satisfactory retinal illumination which in turn provides support and respect of the natural circadian cycle. Any solution that sets out to address the retinal dopamine response should also take into consideration the over-arching

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importance of supporting the natural diurnal circadian rhythm.

The spectral-power distribution of a suitable luminaire must be tunable (processor controlled), emit white light and retain a blue peak at 480 nm offering maximal opportunity to stimulate ipRGC/amacrine cell release of retinal dopamine in concert with preferably the diurnal cycle of the human experience of sunrise to sunset. Further, the blue peak of 480 nm being higher of a morning is preferably reduced over the period of a day's exposure more or less linearly so that by late afternoon there is minimal radiation at the wavelength to which ipRGCs are most sensitive, i.e., 480 nm. Whilst the governing parameters in this solution are based on wavelength and luminance over time, it is for convenience reasonable to describe it here in broad terms that this solution would display a higher CCT of a morning ($\sim$ 5000 K) and a reduced CCT of an afternoon ($\sim$ 3000 K).

Design of the LED Spectral Power Distribution

Adequate exposure to sunlight may be limited for various reasons. In some circumstances, it is logistically challenging to achieve exposure to an ideal dose of daily sunlight exposure. In Europe, myopic progression has been measured to increase significantly in winter months and less so in summer months [25]. Shorter day length is one key factor restricting available ambient light to support the emmetropization process. Research of attitudes to exposure to sunlight amongst Chinese and Korean females in Australia revealed a preference to limit exposure times. In summary, "*They believed that fair skin was more beautiful than tanned skin. They reported that beauty was the reason for active avoidance of sunlight exposure*"[26]. Some schools are now multi-storied- available ambient sunlight in classrooms will depend on the building's aspect and the window orientation to the sun's rays and seasonal variation of solar altitude [27]. Conceivably, not all classrooms will experience an abundance of sunlight all year round with winter months the most likely to be lacking.

Correction of the myopic response to inadequate sunlight and generation of retinal dopamine, begins with triggering the necessary retinal ipRGC/amacrine cell responses that sunlight would otherwise provide. Such a solution must be designed safely cognizant of the potential risk from the blue-light-hazard and exposing the retina to wavelengths in the range of high-energy-visible light (HEV) 415–455 nm for any extended period.

It is not within the scope of this paper to present the arguments relating to this subject in depth, however the proposed solution recognizes and observes these risks[28]. There is a growing awareness in the cell biology community concerned with eye-radiation exposure that the current standards provide a context of measurement that is temporally too limited. ANSI/IESNA RP-27 and IEC/EN 62471 2008 limits exposure times in measuring retinal damage from blue light to 10000 seconds (approximately 2.75 hours). Current eye-related research on blue-light-hazard employs cytological methods of observation that measure profound changes in retinal structure under laboratory conditions but over time frames of 36 hours or more when exposed to blue-LEDs with SPD in the range of high-energy-visible light (415–455 nm). Importantly, this author notes that more recent published laboratory research has identified retinal changes to HEV exposure at luminance levels within the expected range of human experience.

Consideration must be given also to the greater transparency of younger eyes [29] and scenarios where this solution may be deployed (kindergartens, schools and offices). It is essential that protection of the retina from HEV is made a priority in this solution, particularly when offered as a therapeutic benefit. Equally importantly, any light source with a blue peak at 480 nm should be tunable in order that the spectral power distribution and luminance can be altered to respect the natural systemic circadian rhythm. The blue peak should decrease over time essentially following the natural changes in the sun's spectrum consistent with the time between sunrise and sunset.

Wavelength, Luminance and Time: an example of a tunable LED algorithm

Morning Parameters: (9.00am–11.00am) see Figure 5

- Lux: 600
- CCT: 5000 K
- Dominant Wavelength: 480.7 nm

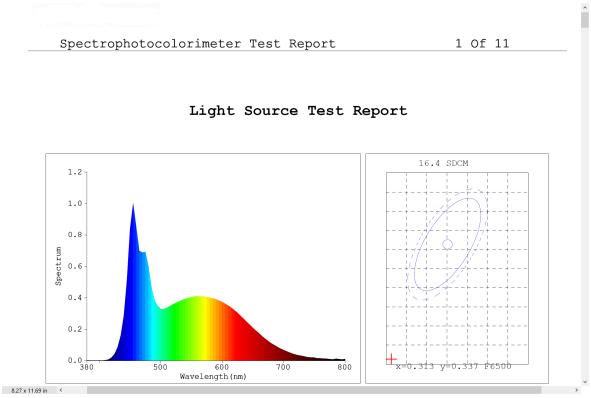

Figure 5: Spectral Power Distribution for 9am–11.00am.

Mid-day Parameters (11.00am–1.00pm) see Figure 6

- Lux: 450
- CCT: 3300 K
- Dominant Wavelength: 587 nm

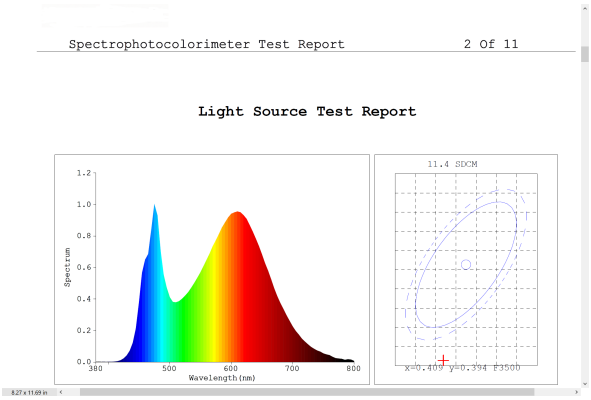

Figure 6: Spectral Power Distribution for 11.00am–1.00pm.

Afternoon Parameters (1.00pm–5.00pm) see Figure 7

- Lux: 350
- CCT: 2600 K
- Dominant Wavelength: 584 nm

Hardware

Supporting the retinal and systemic circadian rhythm requires variation in three fundamental parameters:

- Wavelength
- Luminance (Lux)
- Time

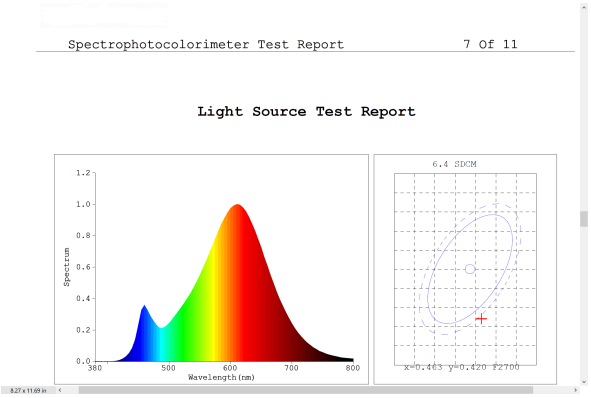

Figure 7: Spectral Power Distribution for 1pm–5.00pm.

To manage these variables, LED luminaires offer a convenient and available solution when combined with processor and software control. Sophisticated software control solutions for LED modules are available as “off-the-shelf” items.

The spectral power distributions in the previous figures were obtained under laboratory conditions from the device featured in the Appendix (Figure 8. Laboratory Luminaire for Assessment of Spectral Power Distribution).

The device illustrated was a simple design to allow accurate measurement of the spectral power distribution and to observe the nature of the light produced. There is no particular limit to the design of a functional luminaire to accommodate the LED source(s) described. Currently however, solid-state LEDs are not widely available that provide the spectral power distribution required here. LED sources with a blue pump and phosphor coating, by virtue of the dipole effect of the blue photons causing excitation of the yellow phosphor, white light is typically produced with a blue peak within the potentially blue-light-hazard range for human eyes at 440–450 nm. There is much scope for the production of a tunable solid-state LED light source that has a blue peak at 480 nm which will still render light ‘white’ to the human eye with a comparable CRI to current LED technology and with a blue peak shifted from the hazardous range. When deployed to act as lighting to prevent myopia, the cardinal variables of wavelength, luminance and time should be strategically adjusted in parallel with the diurnal solar cycle to entrain and support the circadian rhythm. The elevated peak of 480 nm of a morning reducing lineally during the day with a sum of light exposure approaching an average of 14 000–15 000 lux–hours per week ensures appropriate stimulus of both retinal dopamine

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response and entrainment of the natural circadian rhythm.

Discussion

Growth of the human eye is a perfectly normal event from the age of two years (rapid eye growth) to nine (slow eye growth). By the age of nine years, the human eye should have reached emmetropia and normalization of axial length. Under normal day/night exposure and provided with adequate light rich in indigo-blue wavelengths of $\sim$ 480 nm for at least a part of the solar day, the eyes will naturally maintain a state of emmetropia or 'no visual error'; that is no optical correction will be necessary to render an in-focus retinal image. It is a complex process and quite remarkable given that that there is wide variation in the optical properties, particularly focal lengths, of the cornea and crystalline lens that require precise adjustment of eye-length to achieve a clear retinal image.

Not uncommonly, corneas with a central radius that vary significantly from the human average of 7.8 mm are to be found associated with an eye with little or no refractive error. This, despite the fact that the cornea contributes around 44 Diopters out of a total power of 60 Diopters of the total power of the (average) eye; a variation of only 2 or 3 percent of corneal power (from average) would arithmetically vary the refractive power of the eye by about 1 Diopter. Clinicians routinely measure however wide variations in corneal power amongst the cohort of their patients without seeing a commensurate association with visual error. The eye and brain have co-operatively matched corneal power and axial length to render the eye emmetropic. This represents the power of the emmetropization process that can be harnessed by appropriate exposure to requisite wavelengths and luminance levels.

There are currently various methods available to effectively intervene in the attempt to reduce progression of myopia. Recent research has highlighted the use of low-dose atropine eye drops [30]. In the case of atropine, the side effects of blurred vision and a heightened awareness of glare notwithstanding, the benefit is typically lost when the atropine drops are stopped. The most efficacious treatment using low-dose atropine, showed a 2.00 Diopter increase in myopia one year after ceasing the treatment.

In my hands, the prescribing of multi-focal spectacles and historically before that, bifocal spectacles, helped to slow the progression of myopia in the eyes of younger patients most often followed for the period of their schooling and sometimes beyond. These approaches have some merit however they are an attempt to remedy the problem post-onset. These interventions are also costly and in the case of atropine eye drops, not without side -effects.

Visual deprivation studies over many decades has contributed to the view that provision of a clear retinal image is an essential step in providing the necessary conditions for the brain and eyes to self-regulate for an optically correct axial length. Multiple studies [31] using form deprivation or lens-induced blur to one eye of laboratory animals (birds and mammals) typically shows the control eye unaffected by the treatment. A clear retinal image protects the eye against development of any significant visual error. The outcome for the intervention eye universally shows both form and lens induced blur generate a myopic form of ametropia with remarkable effect and in a short period of time.

The initial pupillery response to a visual stimulus is generated by the response of the visual sensory elements, rods and cones. Within a second or less of this initial response, the ipRGCs fire their action potentials to then maintain pupil size (the pupil being slightly more dilated than with the initial pupillery rod/cone response), subject to retinal illuminance. Providing the ipRGCs with the optimal wavelength of $\sim$ 480 nm for absorption by their own retinal opsin, melanopsin, ensures maximum pupillery constriction for a given retinal illuminance. Consequently, the ipRGC pupillery pathway that maintains a smaller pupil provides optimal optical conditions which are the most ideal for an in-focus retinal image and minimal higher order aberrations of the retinal image, shown elsewhere to be positively associated with progression in myopia [32].

Recent research by Kearney et al [33] showed a strong association between elevated morning concentrations of melatonin in myopic adults compared to non-myopic adults: "*This study reports for the first time in humans that myopes exhibit higher serum Melatonin concentrations than non-myopes. This may indicate a role for light exposure and circadian rhythm in the human myopic growth mechanism.*" Kearney concluded: "*The results of the present study demonstrate that*

higher serum concentrations of Mel(atonin), measured in the morning, are associated with myopia in young adults".

If we conclude (from Read's research) that myopic subjects are subject to less light exposure, it is an interesting connection to relate this to the elevated melatonin found in myopic subjects. As melatonin inhibits dopamine, there is a reasonable case to make that elevated serum melatonin is inhibiting the activity of retinal dopamine essential for normal eye growth. Another study showed a systemic effect from elevated levels of serum Levodopa, the precursor to dopamine, slowing the development of form deprivation myopia in animal models [34].

Other studies using animal models have shown an association between systemic circulating melatonin, ocular melatonin and the effect of these factors on ocular growth[35]. *Whilst there is strong evidence for the local beneficial retinal/ocular effects of dopamine contributing to eyes maintaining emmetropia, it is logical given the research to date that support of the systemic circadian rhythm with a phased variation in wavelength and luminance over time is another important component of the solution.*

Photo-entrainment of the non-visual eye-brain processes serves the dual purpose of entraining both the *retinal* and *systemic* circadian cycles. At both the local level and at the systemic level, the primary zeitgeber for photo-entrainment (light) is provided at an optimally prescribed *formula* and *dose* subject to *time* of the solar day.

The prior research of Read and Hua, following on from Rose and Morgan, revealed that once an adequate dose of light was provided myopia was lessened in both progression (Read) and incidence (Hua). The work of Hua was outstanding as it showed that simply increasing room illumination offered a remedy in the context of prior research targeting the beneficial effects of sunlight. Consider also that Hua deployed fluorescent lights which caused a positive outcome. Being tunable and with an optimized spectral power distribution, LED illumination offers a more idealized solution that can be prescribed to respect, support and entrain the circadian rhythm. The exhaustive work over many years by laboratory researchers revealed the vital role of the retinal dopamine response in controlling eye growth. Unraveling the neurobiology and neuro-anatomy of this system over time has helped greatly explain both the laboratory results, field results and epidemiology of myopia.

Myopia is at epidemic levels in East Asia and the trend is following in other developed and developing nations. Left unchecked, myopia will effect at least half the world's population by 2050. Of these, ten percent will suffer from high myopia and be at risk of serious vision loss in later years of life. This equates to 490 million people of the global population estimated to be 7.9 billion at that time. Urbanization of us as a species offers an audience that requires artificial illumination. The evidence suggests there are strong grounds to recommend it is designed to improve eye health.

Acknowledgements

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Appendix

Figure 8: Laboratory Luminaire to Assess Spectral Power Distribution.

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References

[1] Brien A. Holden,Timothy R. Fricke, David A. Wilson, Monica Jong, Kovin S. Naidoo, Padmaja Sankaridurg, Tien Y. Wong, Thomas J. Naduvilath, Serge Resnikoff,(2016). Prevalence in Myopia and High Myopia and Temporal Trends 2000 through 2050. Ophthalmology. 2016 May;123(5): pp. 1036–42. doi: 10.1016/j.ophtha.2016.01.006.

[2] Ibrahim F. Hepsen, Cem Evereklioglu, Hüseyin Bayramlar(2001). The effect of reading and near-work on the development of myopia in emmetropic boys: a prospective, controlled, three-year follow-up study Vision research Volume 41, Issue 19, pp. 2511–2520

[3] A. Bowling, Mode of questionnaire administration can have serious effects on data quality. Journal of Public Health, Volume 27, Issue 3, 1 September 2005, Pages 281–291, https://doi.org/10.1093/pubmed/fdi031

[4] K. Zadnik. Myopia Development in Childhood Optometry and Vision Science The Glen A Fry Award Lecture August 1997.

[5] Edward Mountjoy, Neil M Davies,Denis Plotnikov, George Davey Smith, Santiago Rodriguez, Cathy E Williams, Jeremy A Guggenheim, Denize Atan. Education and myopia: assessing the direction of causality by Mendelian randomisation BMJ 2018;361:k2022 http://dx.doi.org/10.1136/bmj.k2022

[6] Kathryn Rose, Ian Morgan, J. Ip, A. Kifley, S. Huynh, W. Smith, P. Mitchell. Outdoor activity reduces the prevalence of myopia in children. Ophthalmology. 2008 Aug;115(8): pp. 1279–85. doi: 10.1016/j.ophtha.2007.12.019. Epub 2008 Feb 21

[7] Richard A. Stone, Ton Lin, Alan Laties, P. Michael Iuvone (1989). Retinal dopamine and form deprivation myopia. Proc. Natl. Acad. Sci. U. S. A: 86, pp. 704–706.

[8] Czeisler C, Shanahan T, Klerman E, Martens H, Brotman D, Emens J, Klein T, Rizzo J. Suppression of melatonin secretion in some blind patients by exposure to bright light. New Eng J Med 332, 6 (1995)

[9] Elise Drouyer, Ouria Dkhissi-Benyahya, Christophe Chiquet, Elizabeth WoldeMussie, Guadalupe Ruiz, Larry A. Wheeler, Philippe Denis, Howard M. Cooper. Glaucoma Alters the Circadian Timing System. Chédotal A, ed. PLoS ONE. 2008;3(12):e3931. doi:10.1371/journal.pone.0003931.

[10] F. N. Ross-Cisneros, C. La Morgia, J. Hannibal, M. N. Moraes, M. N. Moraes-Filho, V. Carelli, A. A. Sadun; Melanopsin-Containing Retinal Ganglion Cells are Partially Spared by Neurodegeneration in Leber's Hereditary Optic Neuropathy. Invest. Ophthalmol. Vis. Sci. 2009;50(13):2559.

[11] Foster, R.G., Provencio, I., Hudson, D. et al. J Comp Physiol A (1991) 169: 39. https://doi.org/10.1007/BF00198171

[12] Bergson DM, Dunn FA, Takao M (February 2002). "Photo-transduction by retinal ganglion cells that set the circadian clock". Science. 295 (5557): 1070–3

[13] Provencio I, Rodriguez IR, Jiang G, Hayes WP, Moreira EF, Rollag MD (January 2000). A novel human opsin in the inner retina. The Journal of Neuroscience. 20 (2) 600–605

[14] Prigge C, Yeh P, Liou N, Lee C, You S, Liu L, McNeill D, Chew K, Hattar S, Chen S, Zhang D. ipRGCs Influence Visual Function through Retrograde Signaling in the Retina. The Journal of Neuroscience, July 6, 2016 • 36(27):7184–7197

[15] Enezi, J.A., Revell, V., Brown, T., Wynne, J., Schlangen, L., Lucas, R., 2011. A "melanopic" spectral efficiency function predicts the sensitivity of melanopsin photoreceptors to polychromatic lights. Journal of Biological Rhythms, 26(4), pp.314–323

[16] Ronald G. Gregg, Maureen A. McCall, Stephen C. Massey (2013). Retina, Fifth Edition; Function and Anatomy of the Mammalian Retina, Ch 15 pp 360–400.

[17] Sumaya I, Byers D, Irwin L, Del Val S, Moss D. Circadian-dependent effect of melatonin on dopaminergic D2 antagonist-induced hypokinesia and agonist-induced stereotypes in rats. Pharmacology Biochemistry and Behavior Volume 78, Issue 4, August 2004, Pages 727–733

[18] LeGates T and Altimus C. Measuring circadian and acute light responses in mice using wheel running activity. J Vis Exp. 2011 Feb 4;(48). pii: 2463. doi: 10.3791/2463

[19] Zhou X, Pardue M, Iuvone P, Qu J. Dopamine signaling and myopia development: What are the key challenges? Progress in Retinal and Eye Research Volume 61, November 2017, 60–71

[20] Feldkaemper, M and Schaeffel F. An updated view on the role of dopamine in myopia. Experimental Eye Research Volume 114, September 2013, Pages 106–119

[21] Norton T. and Swiegwart J. Light levels, Refractive Development, and Myopia — A Speculative Review. Experimental Eye Research Volume 114, September 2013, Pages 48–5

[22] Read SA, Collins MJ, Vincent SJ. Light exposure and eye growth in childhood. Invest Ophthalmol Vis Sci. 2015; 56: 6779–6787

[23] Hua W J, Jin J X, Wu X Y, Yang J W, Jiang X, Gao G P and Tao F B. Elevated light levels in schools have a protective effect on myopia. Ophthalmic Physiol Opt 2015; 35: 252–262

[24] Ayaki M, Torii H, Tsubota K, Negishi K. (2016) Decreased sleep quality in high myopia children. Scientific Reports. 6:33902. doi:10.1038/srep33902

[25] Cui D, Trier K, Munk Ribel-Madsen S. (2013) Effect of day length on eye growth, myopia progression, and change of corneal power in myopic children.Ophthalmology;120(5):1074–9

[26] Jang H, Koo F, Ke L, Clemson L, Cant R, Fraser D, Seibel M, Tseng M, Mpofu E, Mason R, Brock K. Culture and sun exposure in immigrant East Asian women living in Australia. Women Health;53(5):504–18

[27] https://www.dailytelegraph.com.au/newslocal/parramatta/designs-for-the-states-first-highrise-public-high-school-in-parramatta-unveiled/news-story/526cd42ac12a511959cc7e7fdf9c5c3e

[28] Imene Jaadane, PierreBoulenguez, SabineChahory, SamuelCarré, Michèle Savoldelli, LaurentJonet, Francine Behar-Cohen, Christophe Martinsons, Alicia Torriglia(2015). Retinal damage induced by commercial light emitting diodes (LEDs). Free Radical Biology and Medicine 84 373–384 https://doi.org/10.1016/J.FREERADBIOMED.2015.03.034

[29] Behar-Cohen F, Martinsons C, Viénot F, Zissis G, Barlier-Salsi A, Cesarini JP, Enouf O, Garcia M, Picaud S, Attia D. Progress in Retinal and Eye Research 30 (2011) 245–246

[30] Tan D. Symposium 32: Hot Topics 2015, AAO 2015, Las Vegas

[31] Phelps-Brown N. Koretz J. and Bron A. The development and maintenance of emmetropia. Eye (1999) 13, 83–92

[32] Takahiro Hiraoka, Junko Kotsuka, Tetsuhiko Kakita, Fumiki Okamoto and Tetsuro Oshika. Relationship

between higher-order wavefront aberrations and natural progression of myopia in schoolchildren. Scientific Reports Volume 7, Article number: 7876 (2017) doi:10.1038/s41598-017-08177-6

[33] Kearney S, O'Donoghue L, Pourshahidi LK, Cobice D, Saunders KJ. Myopes have significantly higher serum melatonin concentrations than non-myopes. Ophthalmic Physiol Opt 2017; 37: 557–567.

[34] Mao J, Liu S, Qin W, Li F, Wu X, Tan Q. Levodopa inhibits the development of form-deprivation myopia in guinea pigs. Optom Vis Sci. 2010 Jan;87(1):53–60. doi:10.1097/OPX.0b013e3181c12b3d

[35] Summers Rada J, Wiechmann A. Melatonin Receptors in Chick Ocular Tissues: Implications for a Role of Melatonin in Ocular Growth Regulation. Investigative Ophthalmology and Visual Science January 2006, Vol.47, 25–33. doi:10.1167/iovs.05-0195

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Implications for Human-Centric Lighting Design in Tropical Nursing Homes: A Pilot Study

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Abstract

For the elderly people, adequate environment to compensate for increasing frailty and sensory loss are crucial. Normal age-related changes to the eye decrease the amount of light reaching the retina impacting both vision and circadian rhythm. Some attempts have been made recently to conduct white-tunable lighting and vary lighting levels and CCT for health and wellness. However, how to translate such Human-centric Lighting (HCL) concepts proven in laboratory studies into built environments are still in early stage and lack of largely proven practices and strategies on an operational level. This research project aimed to explore HCL design strategies in nursing homes in Singapore. Firstly, state of the art HCL and aging studies were discussed. We then captured the views to illustrate a HCL framework in a tropical context, whereby the quantitative and qualitative approaches were considered. The preliminary design strategies were developed based on this framework and exemplified in a selected nursing home in Singapore. Also, pre-/post implementation user surveys together with quantitative evaluations (involving horizontal and corneal illuminance measurements) were conducted for assessing the performance of the HCL design strategies. These pilot study findings provide initial insight into HCL design-related knowledge and serve as the solid basis towards the HCL best practices in the environment of nursing home in Singapore.

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Introduction

For the elderly people, adequate environment to compensate for increasing frailty and sensory loss are essential. Normal age-related changes to the eye decrease the amount of light reaching the retina impacting both vision and circadian rhythm. While typical nursing homes provide insufficient lighting, nursing home residents with greater visual impairment perceive far less bright light exposure for circadian rhythm. That leads to the increase of residents' falls, hip fractures, daytime behavior and sleep problems, etc. Nontheless, how to translate the HCL concepts proven in laboratory studies into built environments, including hospitals and nursing homes, are still in early stage and lack of largely proven practices and strategies on an operational level. Specifically, the necessary requirements for the development and effectiveness of control system for HCL in nursing homes have not been formulated in a rigorous and reliable manner.

To date, the designs of lighting systems in nursing homes are primarily made to support visual acuity for staff and secondly to minimise hazards such as staircases. However, to obtain proper visual sharpness and better contrast people of older age require heightened light levels due to age-related failing vision. Furthermore, the nursing home environments are often purpose- made for hygiene, cleanliness and safety and ignore that light sources produce substantial glare due to shiny floors/surfaces and inappropriate light at night disrupts not only sleep but also the timing of the body clock, with negative consequences for cognition and emotions. Properties of current lighting systems are inflexible and not designed to take non visual effects of light into account for older people's wellbeing in nursing homes.

In the last two decade, much has been learned regarding the non-visual effects of light on human circadian entrainment. Light synchronizes physiological and psychological rhythms to the 24-hour rhythm of the environment [1][2]. Light has also acute alerting and activating effects [3], can affect mood [4], and, when applied at night, suppresses melatonin production [5]. These are some examples of the non-visual effects of light in humans. Studies of the biological clock have shown a reduced neuronal activity in the SCN of the elderly, especially after the age of 80 [6], and reduced circadian rhythm amplitude after the age of 50 [7]. This suggests that, at a molecular level, the SCN becomes less responsive to entrainment stimuli such as light-induced neural signals from the retina. Further, it is suggested that some of the neural processes involved in the entrainment process might be dysfunctional or less effective as we age [8]. Thus, the elderly (specifically those with dementia) commonly suffer from mental and behavioural disorders, such as sleep disturbances, agitated behavior, depression, and risk of falls. Studies [9]–[16] have shown that light therapy supported by professional lighting control system can effectively offset these issues and add to the quality of life (e.g., consolidate rest/activity patterns, improve sleep efficiency, cognition, reduce symptoms of depression and alter the levels of aggressive behaviors) to the elderly with dementia in spatial and temporal dimensions.

How to translate the HCL concepts proven in laboratory studies into system implementation in real built environments, including hospitals and nursing homes, are still in early stage and lack largely proven practices and strategies on an operational level [17]–[18]. There are few past and ongoing pilot research and development efforts that have partially addressed certain aspects of the concerns of this current proposal. Such precedents include "Rigshospitalet, Psychiatric Centre Copenhagen: Research project on Ergonomic Circadian Lighting in psychiatry" [19], "Gateway- evaluating a trial LED Lighting System at the ACC Care Center in Sacramento, CA" [20], "Elderly Care Home in Solingen Germany" [21], and "Improved quality of life for resident dementia patients: St. Katharina research project in Vienna" [22]. In these projects, companies in lighting industry (e.g., OSRAM, Philips Lighting, Zumtobel) worked closely with the academia and healthcare institutes.

In this study, we aim to develop and implement a set of advanced human-centric lighting control strategies to improve the comfort and care of seniors, assist the nursing staff in their nightly rounds, and help residents navigate facility hallways via customizing light exposure scenarios for the residents and staffs.

Approach

Description of the case study area

This pilot study was conducted in a selected residence at level one of the Salvation Army Peacehaven Nursing Home in Singapore. This

residence is an entry-controlled area with natural ventilation, including 3 six-bedded rooms, 3 single-bedded rooms, 1 activity room, 8 toilets, and corridor (Figure 3). There are 21 senior residents with mild dementia resided in this area. In this residence, the lighting system will be retrofitted from conventional 24 W CFL lamps with fixed CCT level (i.e., 4700 K) to 10 W advanced tunable-white LED (2700 K to 5000 K; UGR<19; beam angle 40°) (Figure 3). In addition, the smart lighting control system has been installed to allow for individual luminaire control by mobile app via Bluetooth-based mesh network.

Figure 1: The layout of the selected residence.

Figure 2: The previous and selected luminaires for retrofitting.

Pre-implementation assessment

This step includes pre-implementation user survey, on-site illuminance measurement of original lighting performance for the above-mentioned spaces, namely bedded rooms, corridor, activity room, and toilet. 15 nursing staffs (14 females and 1 male, average age of 35.4 years, average working period of 8.11 years in this nursing home) were selected as participants to provide their feedbacks and investigate the residents' perception variables based on the observation from 15 March to 15 May 2017. The user survey with was conducted in from 15 to 30 May, 2017. Based on the above-mentioned assessments, the conceptual design of the control strategies together with user scenarios was developed. The questionnaires for pre-/post implementations was approved by the IRBs of Singapore Institute of technology and the Salvation Army Peacehaven Nursing Home. We selected 7 locations as reference points for the session of on-site measurement. Also, the illuminance meter (Gossen Mavolux 5032) was used to measure the illuminance in selected reference points.

Benchmarking of available strategies

This step addresses the benchmarking of available strategies in view of different space categories through the lighting simulation tool-ElumTools, as a plugin of Autodesk Revit. Such considered spaces include corridor, single/6-bedded rooms, and activity room. The preliminary simulations were conducted to compare the visual performances of the scenarios with existing CFL and the ones with selected tunable-white luminaires.

Human-centric lighting implementation and fine-tuning

This step includes the installation of the advanced tunable LED luminaire control system in selected site. This system comprises IoT-based tunable LED luminaires with plug-and-play capability, user-friendly interface (involving embedded multiple control interface in smart devices and re-use of wall switch), and advanced sensing technologies (e.g., human motion, movement direction, motionless occupancy, fallen human detection, high temperature). Also, preliminary human centric lighting strategies were implemented, tested, and commissioned (Figure 3). The installation and commissioning period was from 1 June to 15 August 2018. After this step, the settings with new control strategies were operated for two months from 15 August to 15 October.

Post-implementation assessment

In this step, we verified and validated the performance of the human centric lighting strategies via post-implementation user surveys.

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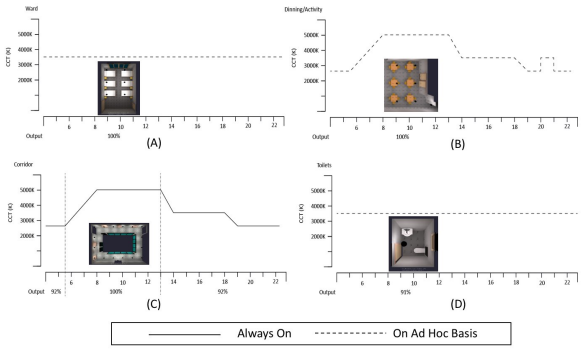

Figure 3: The control scenarios involving luminance output and CCT appearance in the bedded rooms [A], the activity room [B], the corridor [C], and the toilets [D].

The previous-selected 15 nursing staffs, as participants, conducted the user surveys again to provide their feedbacks and investigate the residents' perception variables in view of visual comfort level of the residents and staffs based on the observation during the operation period. The user survey was conducted in from 15 to 31 October, 2017. Also, we measure the illuminance level in selected 7 reference points via the illuminance meter (Gossen Mavolux 5032).

Data analysis and discussion

In this step, we analysed the collected survey data and discussed the results.

Results

The data analysis involved: (i) preliminary simulation-based evaluation, (ii) on-site illuminance comparison based on pre-/post retrofitting, (iii) Data analysis based on pre-/post installations user questionnaires.

Preliminary simulation-based evaluation

The BIM model of the selected residence was built in Autodesk Revit for carrying out a set of simulation with its advanced lighting plugin-ElumTools. Specifically, we evaluated the results of selected areas for further assessment, namely one six bedded room, one toilet, the corridor and activity room. Figure 4 and Figure 5 illustrate the an example of the simulation results pertaining to illuminance distributions of existing CFL luminaire and proposed retrofitted LED with four levels (i.e., 100, 50, 30, 10 percent) and CCT value 2700 K at the floor and reading levels (0 cm and 85 cm) in selected six-bedded room and the corridor. The results suggest that the proposed retrofitted tunable-white LED has a significant visual performance with higher uniformity compared with pre-installation scenario.

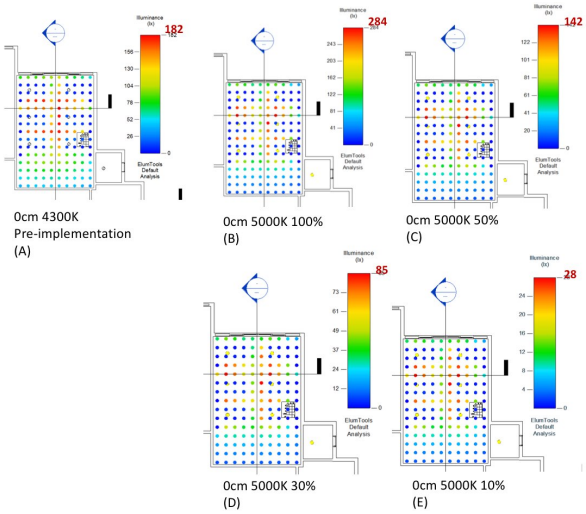

Figure 4: A set of simulation results involving pre-implementation scenario [A] and four sets of post-implementation scenarios with four levels (i.e., 100, 50, 30, 10 percent) and CCT value 2700 K at the floor level (0 cm), namely [B], [C], [D], [E]; unit: lx.

On-site illuminance comparison

In this section, we compared the illuminance measurement data between pre/post- installation scenarios in this residence. As previously mentioned, we have selected two reference points in one six-bedded room (B1, B2), two points in the corridor (C1, C2), two points in the activity room (A1 and A2), and one point in the selected toilet (T1) (see Figure 6). The comparison results are arranged in following tables in accordance with the previously described spaces, namely bedded room, toilet (see Figure 7), corridor,and activity room (see Figure 8).

Data analysis

The results of the above-mentioned sessions (i.e., Section 5 and 5) involving 15 participants were analysed in terms of three categories pertaining to: (i) lighting experiences, (ii) feedbacks and (iii) investigation of the residents' perception variables in temporal (i.e., day and night) and spatial (involving bedded room, corridor, toilet, and activity room) approach based on their observation. Thereby, the five-point qualitative

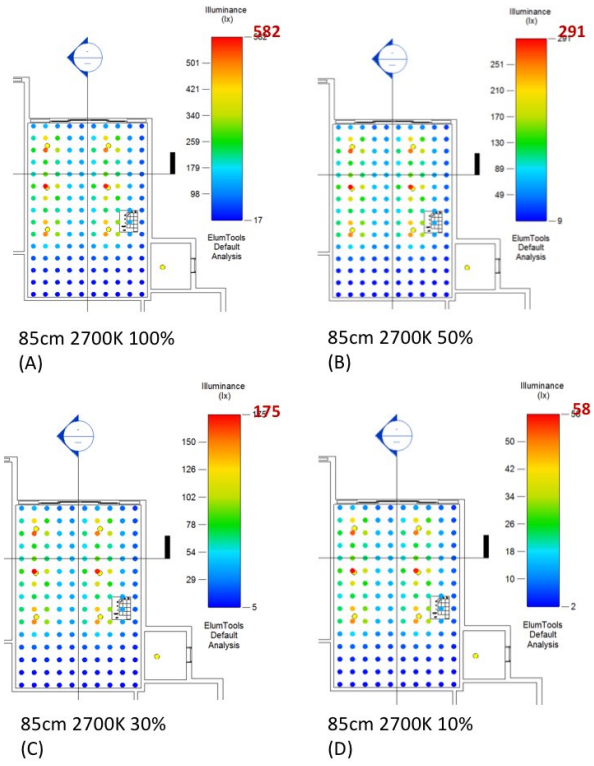

Figure 5: A set of simulation results involving pfour sets of post-implementation scenarios with four levels (i.e., 100, 50, 30, 10 percent) and CCT value 2700 K at the reading level (85 cm), namely [A], [B], [C], [D]; unit: lx.

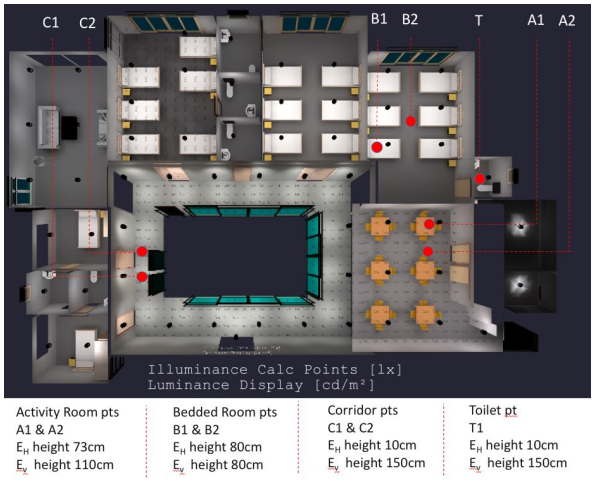

Figure 6: The locations of the measurements points with height information.

Likert scale of the questionnaire was further converted to numerical values (from 1 to 5). Initial results of the analysis if these sessions are given in the following Figures as mean values. In addition, we conducted two tailed t-test to better evaluate the significant difference between pre and post-retrofitting data. Figure 9 (mean values) compares the evaluation results regarding their lighting experiences in bedded room. As the results shown in Figure 9 imply, HCL solution in

Ward/ bedded room	Scenarios	Previous	Retrofitted
	Period	Ad hoc basis	
	Output	100%	75%
	CCT	4700K	3500K
B1	Eh	21	26
	Ev	18	22
B2	Eh	25.8	18.7
	Ev	16	13.6

Toilets	Scenarios	Previous	Retrofitted
	Period	Ad hoc basis	
	Output	100%	91%
	CCT	4700	3500K
T1	Eh	28.4	191
	Ev	56.1	107

Figure 7: Measurement results in the bedded Rooms and toilets; unit: lx.

Corridor	Scenarios	Previous	Retrofitted		
	Period	0-24h	08-13h	14-18h	17-5:30h
	Output	100%	100%	92%	92%
	CCT	4700K	5000K	3500K	2700K
C1	Eh	40	380	245	216
	Ev	18	199	122	109
C2	Eh	42	220	135	105
	Ev	56	85	54	46

Dinning/ Activity Room	Scenarios	Previous	Retrofitted				
	Period (Ad hoc basis)	0-24h	8-13h	14-18	17-20	20-21h	21-5:30
	Output	100%	110%	100%	100%	100%	100%
	CCT	4700	5000K	3500K	2700K	3500K	2700K
A1	Eh	75	582	600	515	600	515
	Ev	33	111	115	92	115	92
A2	Eh	92.7	170	156	120	156	120
	Ev	28.8	73	69	52	69	52

Figure 8: Measurement results in the corridor,and activity room; unit: lx.

our study provides the participants with significantly pleasant lighting experiences in bedded room. HCL solution fairs better than CFL in terms of the categories of natural and bright lighting experiences. Figure 10 shows a comparison of their and residents' (via observation) perceptual attitudes in bedded room. As the results shown in Figure 10 imply, the residents are slightly easier to move around during the night. Also, the residents slightly prefer warm white for the color appearance of the lighting in the bedded room during the night. The nursing staffs are slightly more satisfied with the visual environment at night.

Figure 11 and Figure 12 compare the results involving lighting experiences perceptual attitudes

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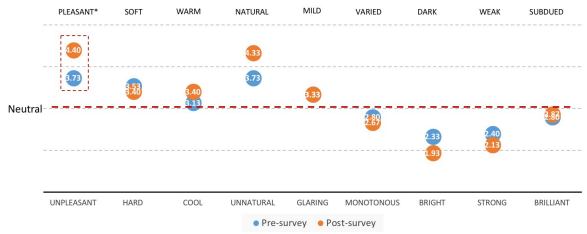

Figure 9: Light experience in the bedded rooms (Mean values, N=15);*p<0.05.

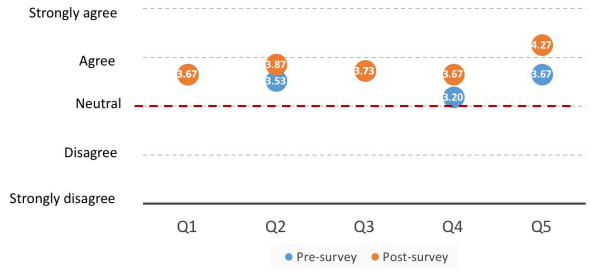

Figure 10: Evaluation results related to the perceptual attitudes in the bedded Rooms (Mean values, N=15).

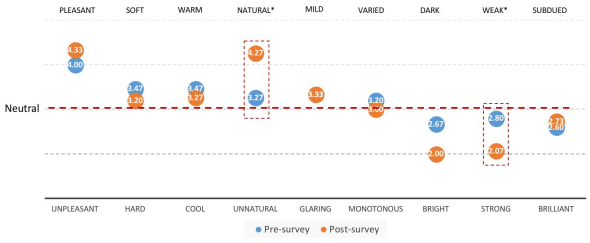

Figure 11: Light experience in the corridor (Mean values, N=15);*p<0.05.

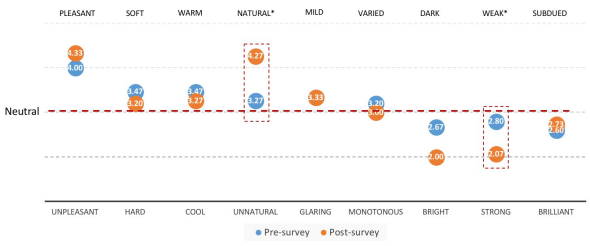

Figure 12: Evaluation results related to the perceptual attitudes in the corridor (Mean values, N=15);*p<0.05.

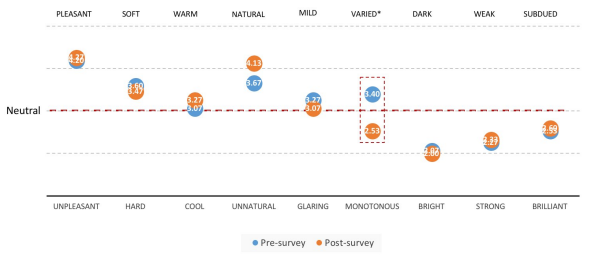

Figure 13: Light experience in the activity room (Mean values, N=15);*p<0.05.

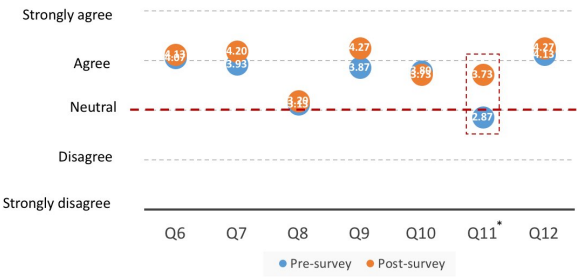

Figure 14: Evaluation results related to the perceptual attitudes in the activity room (Mean values, N=15);*p<0.05.

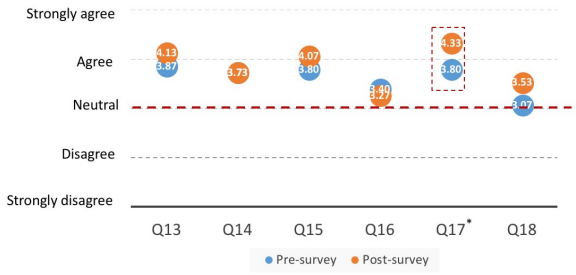

Figure 15: Evaluation results related to the perceptual attitudes in the toilet (Mean values, N=15);*p<0.05.

in the corridor while Figure 13 and Figure 14 do the same for the activity room. As the results shown in Figure 11 imply, HCL solution in our study provides the participants with significantly natural and strong lighting experiences in the corridor. HCL solution in our study provides more pleasant and bright lighting experiences in the corridor. The results show that staffs and residents are with AGREE ratings regarding the sufficient and uniformed brightness of the lighting during the day and night. As the results shown in Figure 12 indicate, the residents and staffs significantly prefer cool white in the corridor during the day. Also, residents slightly prefer warm white during the night while the staffs significantly prefer warm white during the night. As the results shown in Figure 13 imply, HCL solution provides the participants with significantly more monotonous lighting experiences in activity/dining room. HCL solution fairs better than CFL in terms of the categories of natural lighting experiences. As the results shown in Figure 14 imply, the staffs significantly prefer warm white for the color appearance of the lighting in the activity room during the night while the residents remain neutral. The residents are slightly more comfortable with light conditions in activity room thru the whole day. The residents slightly prefer cooler white during the day. No significant difference for task performance of residents

during the day and caregivers during the night. Figure 15 related to the comparison of their and residents' (via observation) perceptual attitudes in the toilet. The participants left AGREE ratings in terms of the clear path to the toilet due to the sufficient brightness of the HCL lamps through the whole day. The participants are with neutral rating in terms of warm white for the color appearance of the lighting in the toilet during the night. As the results shown in Figure 15 portray, the residents significantly prefer cool white for the color appearance of the lighting in the toilet during the day. Also, the glare has been slightly restrained.

Limitation

In our research efforts, computational lighting simulations and empirical measurements were successfully applied for the comparative studies. However, the results could be further compared for all the spaces instead of selected rooms and reference points. Also, in order to better evaluate the impacts of HCL lighting, the supplementary data (involving the body health) of the senior with mild dementia collected via FDA-approved wearable devices could be included in future studies.

Concluding remarks

As the regular circadian rhythm is timely required for those senior with mild dementia and nursing staffs with long-term working hours, it is necessary to specify the circadian practices in the nursing homes based on our findings in previous sections, whereby two primary focus strategies are discussed as below. Firstly, the effective methods to maintain the circadian rhythm should be further explored. Such example includes the optimization of natural light levels with the replacement and/or supplement of electric lighting to artificially stimulate the human circadian system. Thus, the natural light and dark cycles are enhanced to facilitate sleep while natural light spectrum shift with the supplement of artificial lighting over the 24 hours are conducted. Potential applicable spaces in the nursing homes include ward bedded rooms, non-work related windowless environments, common areas, communal environments where relaxation is emphasized. In addition, for such gloomy space with poor daylight penetration, advanced dynamic lighting control systems could be applied to artificially emulate a cycle of dynamic light with natural color shifts timed for circadian support. Also, it may be applied to provide tunable wavelengths of enhanced blue or white light for the purpose of enhancing performance and eliciting specific behavioral outcomes. Potential applicable spaces in nursing homes comprise nursing stations, dispensing pharmacy point, windowless office environments, night shift work areas, and residential settings for better sleep quality management.

This research efforts contributed to above-mentioned two focus strategies. The presented paper demonstrated the preliminary study of a design strategy for HCL systems in nursing homes. Firstly, state of the art HCL and aging studies were discussed. We then captured the views to illustrate the preliminary HCL design strategies in a tropical nursing home, whereby the quantitative and qualitative approaches were considered. The preliminary design strategies were developed and exemplified in a selected nursing home in Singapore. Also, pre-/post implementation user surveys together with quantitative evaluations (involving horizontal and corneal illuminance measurements) were conducted for assessing the performance of the HCL design strategies. These pilot study findings provide initial insight into HCL design-related knowledge and serve as the solid basis towards the HCL best practices in the environment of nursing home in Singapore. For future phases of this research, we will make an attempt to further articulate current effort toward the implementation of HCL for a diversity of space and building types in the Tropics.

Appendix

Questions related to the perceptual attitudes in the questionnaire

Q1. The residents are able to fall asleep within 30 minutes in the bedded room during the night in the past month.
Q2. The residents are able to move about with ease during the night.
Q3. The residents feel safe to move about with the lighting levels during the night.
Q4. The residents prefer warm white for the color appearance of the lighting in the bedded room during the night.
Q5. You are able to work with ease attending to the residents with the lighting during the night.

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Q6. The residents can easily perform their tasks with the light conditions in the activity room during the day.
Q7. The residents are comfortable with the light conditions in the activity room throughout the whole day.
Q8. The residents prefer warm white for the color appearance of the lighting in the activity room during the night.
Q9. The residents prefer cool white for the color appearance of the lighting in the activity room during the day.
Q10. You are able to provide care to the residents in the activity room with current light condition during the night.
Q11. You prefer warm white for the color appearance of the lighting in the activity room during the night?
Q12. You prefer cool white for the color appearance of the lighting in the activity room during the day?
Q13. The residents can see the path to the toilet during the night.
Q14. The lamps provide sufficient and uniformed brightness for the residents in the toilets during the night.
Q15. The lamps provide sufficient and uniformed brightness for the residents in the toilets during the day.
Q16. The residents prefer warm white for the color appearance of the lighting in the toilet during the night.
Q17. The residents prefer cool white for the color appearance of the lighting in the toilet during the day.
Q18. The mirrors and tiles do not cause blinding glare (by reflection) throughout the whole day.
Q19. The lamps provide sufficient and uniformed brightness for the residents in the corridor during the day.
Q20. The residents prefer cool white for the color appearance of the lighting in the corridor during the day.
Q21. The lamps provide sufficient and uniformed brightness for the residents in the corridor during the night.
Q22. The residents prefer warm white for the color appearance of the lighting in the corridor during the night.
Q23. The lamps provide sufficient and uniformed brightness for you in the corridor during the day.
Q24. You prefer cool white for the color appearance of the lighting in the corridor during the day.
Q25. The lamps provide sufficient and uniformed brightness for you in the corridor during the night.
Q26. You prefer warm white for the color appearance of the lighting in the corridor during the night.
Q27. There is little distracting reflection and glare is in the corridor.

Acknowledgment

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References

[1] Rea M.S. and Figueiro M.G. (2016). “Light as a circadian stimulus for architectural lighting”. Lighting Res. Technol. 2016;0:1-14.

[2] Lucas R. J., Peirson S.N., Bersons D. M., Brownl T. M., Cooper H. M., Czeisler C.A., Figueiro M.G., Gamlin P.D., Lockley S. W., O’Hagan J.B., Price L.L. A., Provencio I., Skene D.J.,and Brainard G.C. (2014) “Measuring and using light in the melanopsin age”, Trends Neurosci. 37(1): 1–9.

[3] Cajochen C. (2007). “Alerting effects of light”. Sleep Med Rev. 11(6):453–64.

[4] Burkhalter, H.; Wirz-Justice, A.; Denhaerynck, K.; Fehr, T.; Steiger, J.; Venzin, R. M.; Cajochen, C.; Weaver, T. E.; Geest, S. De. (2015). “The effect of bright light therapy on sleep and circadian rhythms in renal transplant recipients: a pilot randomized, multicentre wait-list controlled trial”, In Transpl Int., doi: 10.1111/tri.12443, volume 28(1), 2015.

[5] Lewy, A. J., Sack, R. L. and Singer, C. L. (1984). “Assessment of treatment of chronobiologic disorders using plasma melatonin levels and bright light exposure: the clock-gate model and the phase response curve”. Psychopharmacol. Bull., 20: 561–565.

[6] Swaab D, Fliers E, Partiman T. The suprachiasmatic nucleus of the human brain in relation to sex, age and senile dementia. Brain Res. 1985;342:37–44.

[7] Hofman MA, Swaab DF. Living by the clock: the circadian pacemaker in older people. Ageing Res Rev. 2006;5:33–51.

[8] Skene DJ, Swaab DF. Melatonin rhythmicity: effect of age and Alzheimer’s disease. Exp Gerontol. 2003;38:199–206.

[9] Lieverse R1, Van Someren EJ, Nielen MM, Uitdehaag BM, Smit JH, Hoogendijk WJ. (2011). “Bright light treatment in elderly patients with nonseasonal major depressive disorder: a randomized placebo-controlled trial”. Arch Gen Psychiatry. 68(1):61–70.

[10] Hanforda N. and Figueiro M. (2013). “Light Therapy and Alzheimer’s Disease and Related Dementia: Past, Present, and Future”, J Alzheimers Dis. 33(4): 913–922.

[11] Alessi CA, Martin JL, Webber AP, Cynthia Kim E, Josephson KR. Randomized, controlled trial of a nonpharmacological intervention to improve abnormal sleep/wake patterns in nursing home residents. J Am Geriatr Soc. 2005;53:803–810.

[12] Ancoli-Israel S, Gehrman P, Martin JL, Shochat T, Marler M, Corey-Bloom J, Levi L. Increased light exposure consolidates sleep and strengthens circadian rhythms in severe Alzheimer’s disease patients. Behav Sleep Med. 2003;1:22–36

[13] Burns A, Allen H, Tomenson B, Duignan D, Byrne J. Bright light therapy for agitation in dementia: a randomized controlled trial. Int Psychogeriatrics. 2007;21:711.

[14] Lovell BB, Ancoli-Israel S, Gevirtz R. Effect of bright light treatment on agitated behavior in institutionalized elderly subjects. Psychiatry Res. 1995;57:7–12.

[15] Hickman SE, Barrick AL, Williams CS, Zimmerman S, Connell BR, Preisser JS, Mitchell CM, Sloane PD. The effect of ambient bright light therapy on depressive symptoms in persons with dementia. J Am Geriatr Soc. 2007;55:1817–1824.

[16] Figueiro MG, Gras LZ, Rea MS, Plitnick B, Rea MS. Lighting for improving balance in older adults with and without risk for falls. Age Ageing. 2012;41:392–395.

[17] Halper M. (2016). “Human-centric lighting set to drastically improve workplace and individual performance”. LEDs Magazine. (Oct 2016). 49–54

[18] Konis K. (2017). “A novel circadian daylight metric for building design and evaluation”. Building and Environment. 113(2017). 22–38

[19] Chromaviso. Research in Circadian Lighting and user evidens. `http://chromaviso.com/en/ergonomic-circadian-lighting/research-in-circadian-lighting/` (20 April 2017, date last accessed).

[20] DOE. Gateway- evaluating a trial LED Lighting System at the ACC Care Center in Sacramento, CA. `https://energy.gov/sites/prod/files/2016/09/f33/2016_gateway-acc.pdf`. (20 April 2017, date last accessed).

[21] Philips Lighting. Elderly Care Home in Solingen Germany. `http://www.lighting.philips.com.sg/cases/cases/healthcare/elderly-care-home`. (20 April 2017, date last accessed).

[22] Zumtobel. Improved quality of life for resident dementia patients: St. Katharina research project in Vienna. `http://www.zumtobel.com/PDB/teaser/EN/Study_Health_and_Care_StKatharina.pdf`. (20 April 2017, date last accessed).

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Full Spectrum LEDs and Indoor Daylight Support for Health and Wellbeing

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Abstract

Daylight is the preferred light source of choice for human centric lighting applications in the built environment, as the human visual system and psycho-physiology has evolved under this environmental condition.

Conventional white LED light sources pump on blue (around 450 nm) and show an unbalanced spectrum with a prominent peak in the shortwave region of the visible spectrum. This disturbed emission might be associated with several discomfort and health issues.

Innovative technologies in optoelectronics based on purple dies and multiple phosphors offer an emission very similar to daylight, particularly indoor after the glazing media.

We propose to consider the light provided by full spectrum LEDs as indoor daylight in building standards and regulations.

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Introduction

Human beings have evolved in nature under the conditions of sunlight. The rhythmicity of the rotation of the Earth around its axis, and of the Earth around the Sun provide the temporal domain of this interaction. The first creates the circadian. This is

Daylight and Artificial Light Sources. Indoor Daylight and Full Spectrum LEDs

In the built environment there are at least three issues directly related to lighting. Daylight, Artificial light and Views. Daylight is the preferred light source as it is our evolutionary driver. From an ecological point of view, this is our most powerful environmental factor. There is no human life without sunlight. From a societal point of view, artificial light is our second light clue. It began first with glazing as a way of preserving the entrance of daylight and to promote the connection with the outdoor world. Even if there is no standardized differentiation between daylight and daylight through glazing, I prefer to call this second one as "Indoor Daylight", where relevant parts of the Sun emission are removed in the ultraviolet and infrared tails. Electric light has become more important in the last century since the advent of incandescent. In the last decade LED lighting has become a revolution for indoor lighting.

In Figure 1 we can see the difference in spectral power distribution (SPD) between daylight and indoor daylight. Figure 2 shows the difference between indoor daylight and a typical blue pumped LED. Figure 3 shows the similitude between daylight and full spectrum LEDs (Seoul SunLike). As we can see in Figure 4, the main differences are that conventional LED do not provide the 420 nm signature that we find in daylight, and the lower amount of melanopic contribution as we will discuss later in this paper.

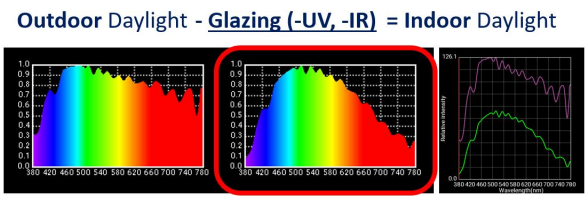

Figure 1: Indoor Daylight: Daylight - Glazing.

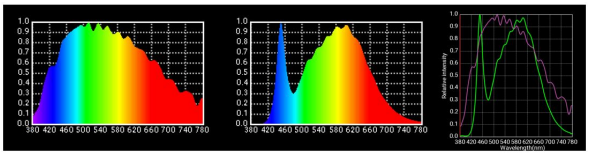

Figure 2: Daylight vs. Blue Pumped LED.

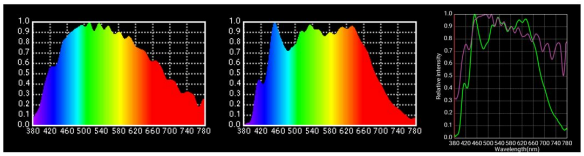

Figure 3: Daylight vs. Full Spectrum LED.

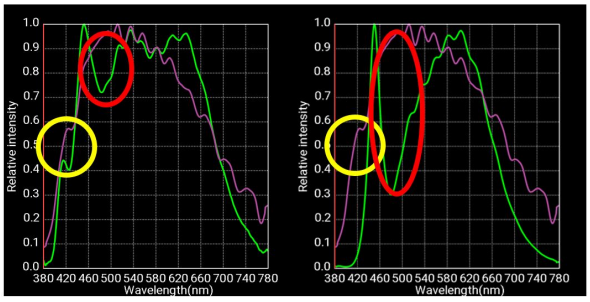

Figure 4: Comparison between Indoor Daylight and full spectrum LED (left) and Indoor Daylight and conventional blue pumped LED(right).

Integrative Lighting / Human Centric Lighting

Before entering the discussion about Human Centric Lighting and health and wellbeing, it is appropriate to properly define the terms. The adequate definition of health and wellbeing, same as performance, alertness, awakeness, etc, even if critical, are out of the scope of this paper. Human Centric Lighting, also known as HCL, has been broadly used in the last years without a consensus about its scope. The only public definition comes from ZVEI (Zentralverband Elektrotechnik- und Elektronikindustrie e.V., the German Electrical and Electronic Industry association).

ZVEI defines HCL as (2016-09): "Unterstützt zielgerichtet und langfristig die Gesundheit, das Wohlbefinden und die Leistungsfähigkeit des Menschen durch ganzheitliche Planung und Umsetzung der visuellen, emotionalen und insbesondere der biologischen Wirkungen des Lichts".

The CIE (Commission International de l'Eclairage, International Commission on Illumination) has recently introduced the term "Integrative Lighting",

to avoid the pervasive (mis-)use of the term HCL, and their definition is as follows (DIS 017:2016, 17-29-030): “Lighting especifically designed to produce a beneficial physiological and/or psychological effect upon humans” (including both, visual and non-visual effects).

What is interesting here is that it considers the non-visual effects of lighting (not only light) in humans, and that the effect should be beneficial. The differentiation between light and lighting is critical. We do not precisely know what is light. What we know is how to deliver it. The way I define lighting is as the “art and science of delivering light”. This comprises not only the light intensity and spectrum (spectral power distribution), but also the directionality, the temporal effects, in terms of timing and dosage, the beholder, and the activities performed. And most important, the interaction between the light sources, natural and artificial, and the architectural spaces.

This conforms what Gibson would have called “non-visual affordances”. The interaction with the architectural spaces and non-visual effects of light(ing) has been considered for the first time in the WELL Building Standard, in the “Light” concept, and more precisely in the “Circadian Lighting Design” feature. And this is what we are going to consider next.

Buildings and Architectural Spaces. The WELL Building Standard Circadian Lighting Design

Most of the building codes and standards consider light as a critical factor in the built environment. The main approach is about energy. A few examples are LEED, BREEAM and Passive Haus. This has been the focus in the last years, how to improve energy efficiency in buildings, with lighting as a main player.

But, how important is energy from a financial point of view? According to the World Green Building Council (WGBC) and the 1/9/90 rule, if we consider the total operational cost of a typical office building for a lifespan of thirty (30) years, we can see that the total impact of energy consumption is one (1) percent! Rental and equipment follows with nine (9) percent. And, most important, people, the occupants of the building, account for ninety (90) percent of the costs over thirty (30) years. So what? Where do we have to focus? There is out of the question that we have to take care of the environment and optimize energy consumption to make better use of our natural resources. But we can not forget human sustainability and total costs. Healthcare costs are critical in modern societies, and improving health and wellbeing of building occupants can not only improve short term productivity and wellbeing, but also reduce long term healthcare costs.

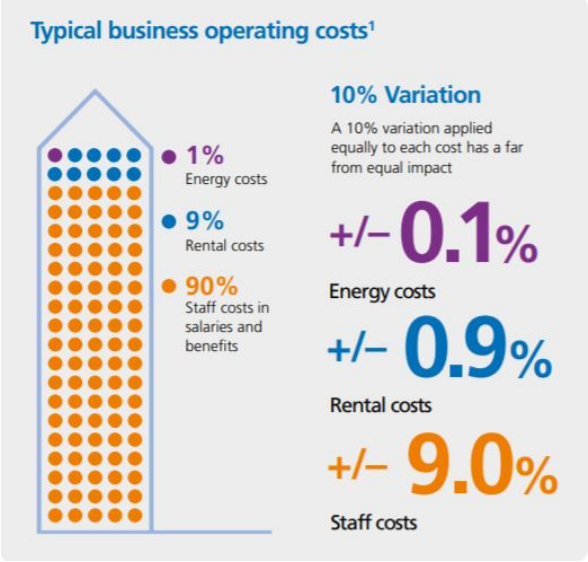

Figure 5: WGBC and the 1/9/90 rule.

WELL is a standard that focuses exclusively in the health and wellbeing of the building occupants. It takes into consideration seven concepts (in version 1, ten in version 2) that directly affect people (Figure 6): air, water, nourishment, light, fitness, comfort and mind.

In the “LIGHT” concept we can differentiate between 11 features and one of them, the most important for HCL, is “Circadian Lighting Design”. This feature takes into account the human circadian rhythmicity, lighitng as a main driver for the human circadian system, the intrinsically photosensitive retinal ganglion cells (ipRGC) as the main underlying mediator for this interaction, the melanopic stimulus as the metric, and offers the equivalent melanopic lux (EML) as the calculation model for the melanopic stimulus. EML is discontinued in version 2, and a new model, the Melanopic Equivalent Daylight Illuminance is introduced, as it has been officially published recently by the CIE (CIE JTC-9 - CIE DIS 026:2018).

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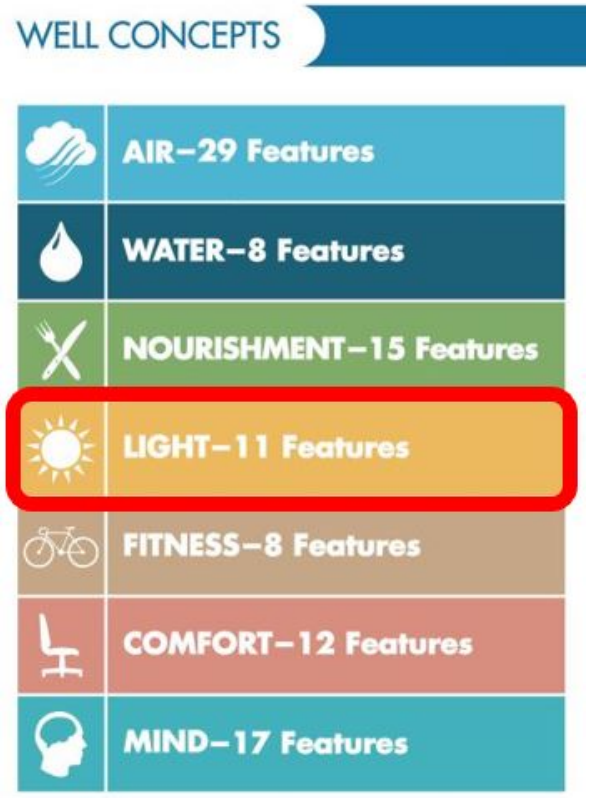

Figure 6: WELL (v1) Concepts.

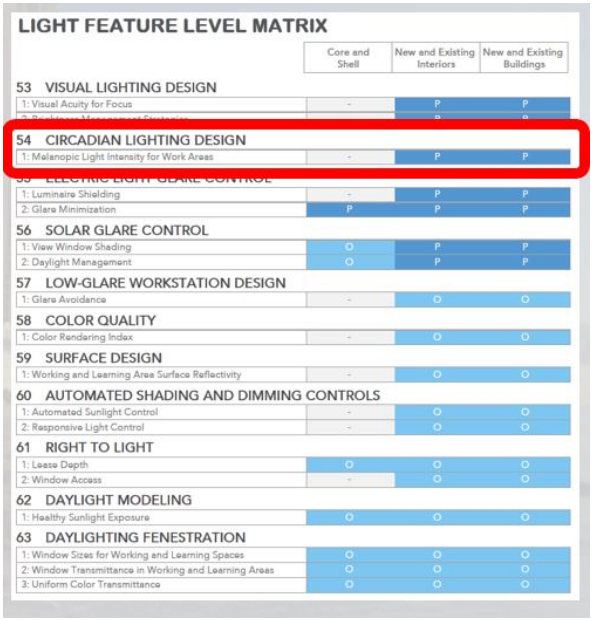

Figure 7: WELL (v1) LIGHT features.

Performance Metric for HCL: Evmel/Eh. An Example with Full Spectrum LEDs

Figure 8 shows how to calculate EML in WELL v1. In the presentation we will expose one example of calculation together with the introduction of a new metric (Figure 9) based on how much illuminance is needed in the workplane to achieve a certain amount of melanopic stimulus in the vertical plane.

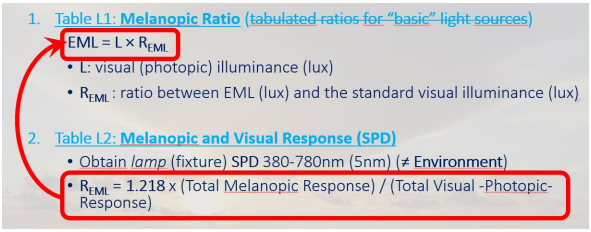

Figure 8: WELL v1 EML calculation.

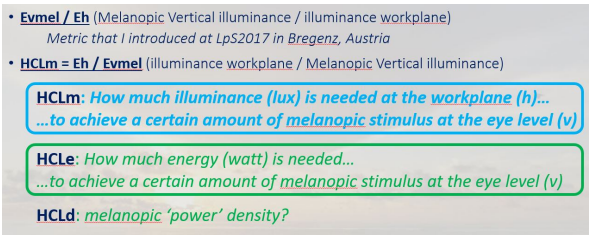

Figure 9: HCLm metric for design performance

Melanopic stimulus metrics limitations

There are many limitations in the melanopic stimulus metrics.

Biology is not behavior in humans, we are not mice: the stimulus is not the effect, there are affective, cognitive, behavioral and allostatic factors, together with aging compensatory mechanisms.

These metric are based on melatonin supression at night, and could be not appropriate to measure effects during daytime. The orexin/hypocretin neuropeptide produced by neurons in the perifornical area and lateral hypothalamus of the brain are responsible for wakefulness and arousal. And extremely important, alertness is not awake-ness and focus.

We have to consider directionality as the light coming from the upper side of the sight is more effective than the light coming from downwards.

Finally, these metrics are not easy to implement for lighting designers, and we are not statistics.

Technology and Design

A lighting system imprints light(ing) in an environment, same as printers print papers.

Lighitng is not anymore about fixtures, it is about Information Technologies, IT (software and networks). Procurement has to move from MEP (mechanical, electrical, plumbing) to IT to really appreciate, implement and pay for the HCL value and benefits.

User interaction/interface and user experience (UX) are critical in HCL, and we need multichannel systems beyond tunable white, with single vs. double/multiple emission.

Glare clashes with melanopic stimulus in conventional design. Dark lighting does not work for HCL. If we do not get light into the eyes, we do not imping the melanopic stimulus. Retrofit is not real HCL, we need to redesign. Light surfaces vs. point sources: larger surfaces provide lower luminances and less glare, at the time that are able to give the melanopic stimulus. Indirect lighting is preferred to direct, the space becomes the third optic.

Finally, daylight is the preferred light source, full spectrum LEDs the closer alternative.

Ethical Questions

Ethical issues will immediately arise with the implementation of HCL interventions. The most conservative fraction of the lighting community promotes the “Do no harm” thesis, the precautionary approach. I am more prone to the proactionary perspective, “To do Good”. My criteria is that we do more harm not doing, than doing with responsibility with the knowledge that we have (even if we do not know the precise underlying mechanisms, do we have to know the why?).

Going into real world applications, as we claim that office workers are going to be more productive, and... are they going to be compensated? More vacation/free time? Higher salaries? Or do the differentiation in outcomes in health are going to be enough to compensate their better performance.

What about schools. There are studies that say that academic performance may be improved with the HCL approach. If students in schools with HCL are going to perform better than students in conventional lighting schools, how is the educational system going to compensate for these differences to become more equalitarian for acceptance thresholds based on scores?

And in healthcare, what is going to happen with insurance systems once they realize that HLC may reduce length of stay of patients and improve the healing process? Are they going to promote HCL in their associated hospitals, pay less to hospitals without HCL? Are we going to see claims derived from longer stays in rooms without views and with bad lighting? What about medical errors if clinicians can reduce their mistakes with proper lighting?

All of these are open question that society will have to address as HCL becomes implemented.

About the lighting industry, this is a multidisciplinary ethical debate. We know that HCL is not about tunable white and about correlated color temperature metrics, neither about color perception. RGB and BY (blue, yellow in conventional LEDs) are fake news for the human visual system and human psycho-physiology. We need to promote specific wavelengths and full spectrum light sources that mimic daylight conditions. Eye health is becoming a huge concern indoors, with a pandemia in myopia and AMD. Both can be improved with proper lighting. Are we going to take action?

We definitely need to promote awareness and education in this field for the different stakeholders: users, decision makers, facilities managers, research, industry and governments. Not doing is the real harm.

Conclusions

The first conclusion is that HCL can not be conditioned by energy efficiency, we are not anymore in the lumen/watt arena, we are facing a new era of (wellness and health)/watt and/or performance/watt... the lumen is dead for HCL.

Other performance metrics, more specific for the built environment, have to be developed to facilitate the implementation of the field in the real world. We proposed last year at LpS2017 one metric that we have evolved this year as the ration between the vertical melanopic illuminance (in terms of EML or M-EDI) and the photopic lux: how much illuminance (in lux) is needed at the workplane (h) to achieve a certain amount of

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melanopic stimulus (not effect, this is another challenge) at the eye level (v).

We have clarified that lighting is not only light, we can not extrapolate conclusions from basic science into real spaces and inhabited environments.

The Exposome, the (architectural) environment, is a key factor in HCL. Standards such as WELL are needed to clarify the HCL horizons. Technology and design are key for successful interventions.

Finally, we should be able to address sooner or later the questions raised by Dr. Richard Wurtman in the sixties of the past century, around fifty years ago: “What kind of light sources should we construct in order to satisfy man’s biological as well as visual needs”, and “an appropriate body should give thought to the ultimate necessity of regulating the espectral composition of commercially available light sources.”

Ethics is critical. The closer we are to nature, the closer we are to ethics, and this can achieved promoting full spectrum light sources closer to daylight (outdoor or indoor).

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by Dr. Michael Kunzer (NOMINEE: LED professional Best Scientific Paper Award 2018), Fraunhofer Institute for Applied Solid State Physics

214 Heat Fluxes and Temperatures in Chip-on-Board LEDs for Different Package Structures and Phosphor Technologies
by Dipl. Phys. Max Wagner, Technische Universität Darmstadt, Laboratory of Lighting Technology

220 Advancements in LED Technology Enabling High-Luminance LEDs
by Dr. Werner Goetz, Lumileds

232 Rapid Evolution of High-Power LEDs Package from SMD to CSP to Direct Mountable Chip
by Denis Xavier, NICHIA Europe B.V.

238 New Human-Centric Lighting Based on TRI-R Spectrum Technology
by Kumpei Kobayashi, Toshiba Materials

244 LED Filaments – A new Technology Enables Classical Design in LED Retrofit Lamps
by DI Markus Hofmann, OSRAM Opto Semiconductors

250 An Introduction of OLED Lighting Technology
by DI Claudia Keibler-Willner, Fraunhofer FEP

256 The Latest Developments in Laser Light Sources For Industry-Leading Luminance
by Julian A. Carey, SLD Laser

262 Linear LED Strip Based on a High Frequency Design
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268 Defining the Spectrum for Your Unique Lighting Application – Spectrum, TM-30-15, and Human Centric LED Sources
by Tom Jory, Luminus Devices, Inc.

Modeling and Quantifying LED Variability

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Abstract

Delphi4LED is an H2020 ECSEL European research project. Its ambition is to create a complete model to assess the performance of entire LED luminaire systems prior to the prototyping phase. This paper presents measurements on 11 royal blue LEDs and 10 Phosphor converted white LED packages of same type. Thermal measurements are presented in details. An advanced statistical analysis methodology used to model how it varies from sample to sample is presented. Results demonstrate that the temperature of LEDs with phosphor varies slightly more than that of their royal blue counterparts. Measured electrical and optical variability and its implication for the White LED on colorimetry, circadian and horticulture perception indexes are also presented at the end of the document. This work will serve as a building base to model variability with the $I - V - L$ multi-domain model used within Delphi4LED.

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Introduction

Delphi4LED [1] is an H2020 ECSEL European research project involving 15 partners across Europe: measurement laboratories, research institutes, software companies and luminaire manufacturers. Program ambition is to deliver a complete model to assess the performance of complete LED luminaire systems even before the prototyping phase. This is achieved thanks to massive characterization and the use of a compact thermal model (CTM) [2] plugged into a multi-domain chip level LED model combining thermal, electrical and optical physics [3]. Besides electrical and optical behaviors, thermal behavior is a key physical phenomenon that has to be taken into consideration to model LED luminaire systems and therefore predict their performance. For the present study, two sets of level 2 packages (starboard Metal Core measurement PCB + LED); one with royal blue LEDs (RB) and another one with phosphor converted white LEDs (PCW) with 5000 K CCT and 70 CRI were measured. Each set consisted of eleven samples, the PCW LEDs contain same type of royal blue LEDs as the RB set. 10 samples of PCW were analyzed in this article, because 1 sample was found to be defective, and was excluded from further analysis. Both sets are measured and analyzed in order to assess and model how level 2 packages manufacturing variability affects its performance, and in particular how thermal behavior is being affected. This paper is organized as follows:

1. General experimental principle used to measure a thermal transient is briefly explained in this part (the methodology is also described in more details in the Appendix). Structure functions description and discussion on results are also proposed here.
2. The statistical methodology used to assess variability of structure functions is described.
3. Monte-Carlo methodology to deliver variability distributions from the CTM that will be used as an input for the multi domain compact model is presented and results discussed.
4. Finally, electrical and optical characterization methodology and experiment details for the two sets of level 2 packages is described. Electrical and optical fluctuation findings comparing the two types of level 2 packages are given and root cause for behavior differences discussed. Implications of variability on colorimetry, circadian and horticulture indexes are also presented.

From Thermal Transient To Structure Functions

Thermal transient testing of semiconductor devices can be completed by carrying out the following steps:

- Thermal sensitivity calibration, which is mapping of V_f forward voltage induced by a steady I_f forward current to an external temperature. In established methods this occurs at a low I_M measurement current, where the T_j junction temperature is approximately the same as the external temperature.
- Powering the device. In this step a high I_H heating current is applied on the device. Having reached thermal steady state, the $P_{el} = I_f \cdot V_f$ electric heating power can be determined. In case of light emitting devices also radiometric and photometric measurements can be carried out in steady state, as defined in standards.
- Switching down and measure a thermal transient.
- Protocol used to obtain the Structure Functions (SF) from the thermal transient measurement is detailed in the Appendix.

Structure functions provide some valuable insight on thermal behavior for the different parts of the level 2 assembly, including LED chip, package and PCB. Thermal resistance is expressing heat conduction and thermal capacitance is expressing energy storage. In low gradient sections a small amount of material having low capacitance causes large change in thermal resistance. These regions have low thermal conductivity or small cross-sectional area. Steep sections correspond to material regions of high thermal conductivity or large cross-sectional area. Changes in gradient correspond to material or geometry changes. In such a way, thermal resistance and capacitance values, geometrical dimensions, heat transfer coefficients, material parameters can be estimated from structure functions without the need for destructive methods such as sectioning.

In Figures 1 and 2 below the structure functions are plotted for the 11 RB and for the 10 good PCW samples, respectively, at T_j = 85 °C and

I_f = 700 mA. These temperature and forward current values were selected as this measurement point is considered to be the closest to real life LEDs use conditions. All the analysis presented in this paper were performed at these conditions.

The median structure function of each type was selected to be calibrated against. The resulting detailed model nominated thermal conductivity parameters tuned so as to demonstrate a good match between simulation model and measurement.

Greater variance was seen in the PCW sample measurements, that might be partially attributed to the variation in the silicone+phosphor depositing process. A ±4% variation in overall R_{thJA} is seen for the RB samples and a ±4.4% variation in overall R_{thJA} is seen for the White samples. It is noted that there is very little variation in the thermal capacitances, the structure function curves are shifted in the horizontal R_{th} axis direction, not in the vertical C_{th} axis direction.

It is anticipated the different thermal footprints will lead to moderately increased variability at electrical and optical level as seen in past work [4].

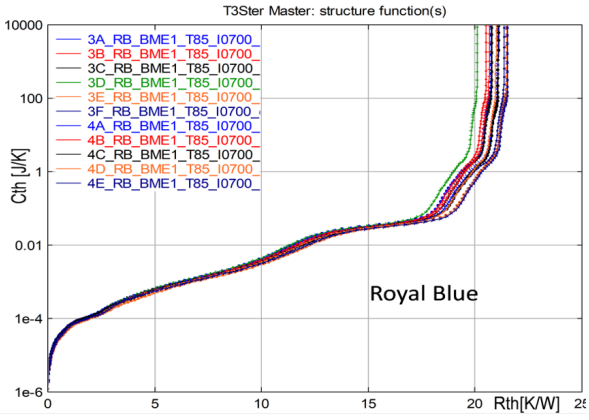

Figure 1: Structure functions of 11 RB samples at T_j = 85 °C and I_f = 700 mA.

Statistical Analysis

From the 11 RB and 10 PCW samples measured, a statistical analysis is proposed in order to understand how each part of the structure function is distributed. Two distinct approaches are proposed.

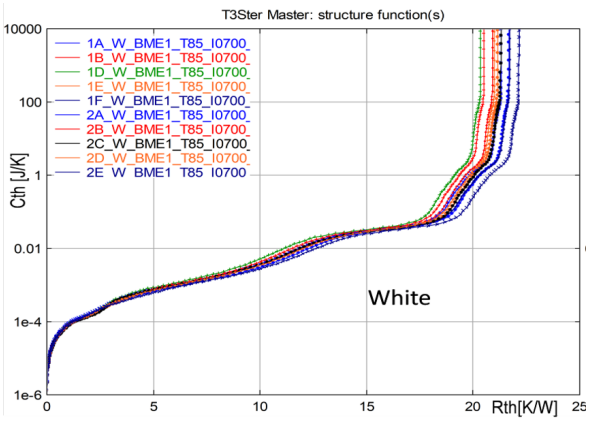

Figure 2: Structure functions of 10 PCW samples at T_j = 85 °C and I_f = 700 mA.

Method 1: From RC ladder and correlation coefficients

First approach uses a solver to minimize a 12 stages RC ladder for each of the 11 structure functions.

As seen in Figures 1 and 2, R_{th} varies much more from samples to sample than C_{th} does. For this approach, we simply assume C_{th} as constant from sample to sample. First step is to subdivide structure functions in 12 stages based on areas of equivalent fluctuation among the 11 samples on the local R_{th} vs C_{th} plot as depicted in Figure 3 below. Local R_{th} is defined as the delta in R_{th} values between two nearest points in structure function plot. This allows us to define 12 C_{th} stages identical for all 11 samples (only first 11 are depicted in Figure 3, last one starts at measurement number 154 at the extreme right of the figure all the way to last measurement number 199). Peak of fluctuation on the right is attributed to the “dry” thermal interface (i.e., without additional thermal grease) between bottom of MCPCB (Metal Core PCB) and the cold plate (cold plate is used to quantify the contributions of different heat transport mechanisms to the thermal conductivity of a certain material). Also, largest, second fluctuation peak starting from the right is attributed to the interface between MCPCB dielectric and MCPCB core. Peak in fluctuation is slightly shifted to the right compared to local R_{th} maximum, located in the dielectric. Second fluctuation peak starting from the left is attributed to voided die attach used to contact LED chip stack to copper layer underneath. Some more details on how structural information can be obtained using cross section scanning electron microscope inspections coupled with FloTHERM™ simulations, and insight on root

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cause for fluctuation profile along the level 2 package can be found in [5].

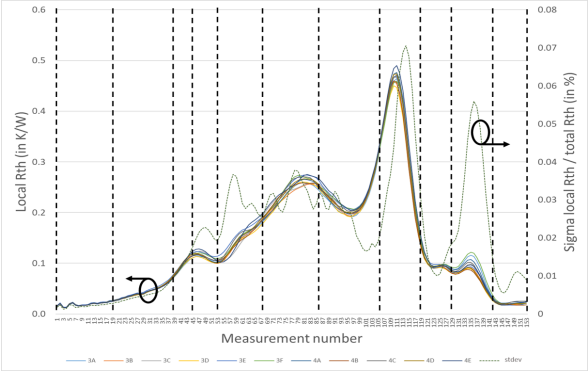

Figure 3: 11 RB samples Local R_{th} (y-axis left, full lines) vs C_{th} and σ Local R_{th} / total R_{th} (y-axis right, dotted line) vs C_{th}. 12 C_{th} stages are defined based on areas of equivalent fluctuation.

Using a solver, one can then minimize error between a 12 stages RC ladder and each of the 11 structure functions as shown in Figure 4.

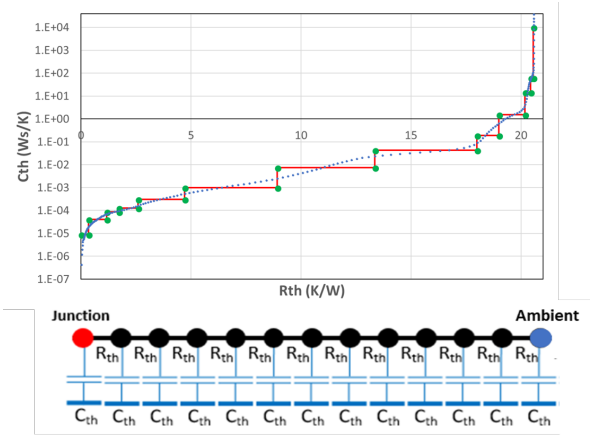

Figure 4: For one of the 11 RB LED samples, structure function and corresponding 12 stages thermal resistor capacitor ladder.

This gives us a set of 12 distinct R_{th} distributions of 11 samples each. Average C_{th} values (upon 11 samples) and these R_{th} values, as well as median and standard deviation of R_{th} are reported in Table 1 below.

Absolute Stdev is the largest for stage 8 (bottom mcpcb circuit + dielectric + top mcpcb core) and stage 10 (dry die attach + top coldplate). It is also pretty high for stage 6 and 7 (bottom Copper layer / body + pads and solder + top mcpcb circuit). Relative Stdev is the largest for stages 10, 11 and 12, corresponding to the cold plate.

Table 2 below compiles the correlation coefficients matrix for R_{th} distributions of stages 1 to 12 as well as corresponding physical layers of the RB

Table 1: RB 12 stages RC ladder average C_{th} and individual samples R_{th} for the 11 RB samples.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10	Stage 11	Stage 12
Average Cth (among 11 samples)	8.5E-06	3.1E-05	4.4E-05	3.9E-05	1.7E-04	6.7E-04	6.2E-03	3.4E-02	1.5E-01	1.4E+00	1.3E+01	4.5E+01
Rth Sample 3A	0.331	0.829	0.546	0.879	2.122	4.203	4.439	4.650	0.988	1.183	0.253	0.137
Rth Sample 3B	0.343	0.857	0.579	0.890	2.112	4.175	4.515	4.554	0.969	0.969	0.242	0.118
Rth Sample 3C	0.340	0.848	0.557	0.950	2.082	4.294	4.592	4.646	0.968	1.033	0.268	0.128
Rth Sample 3D	0.334	0.836	0.553	0.865	2.088	4.202	4.471	4.479	0.961	0.945	0.242	0.091
Rth Sample 3E	0.362	0.904	0.594	0.950	2.317	4.429	4.718	4.715	1.033	1.008	0.248	0.153
Rth Sample 3F	0.341	0.853	0.559	0.930	2.191	4.413	4.674	4.677	1.039	1.255	0.273	0.149
Rth Sample 4A	0.339	0.850	0.567	0.884	2.147	4.266	4.537	4.769	1.011	1.113	0.286	0.099
Rth Sample 4B	0.343	0.858	0.568	0.900	2.114	4.304	4.578	4.562	0.980	0.937	0.240	0.121
Rth Sample 4C	0.335	0.838	0.562	0.906	2.223	4.362	4.607	4.704	0.991	1.045	0.277	0.095
Rth Sample 4D	0.348	0.869	0.590	0.895	2.163	4.336	4.601	4.722	1.004	0.971	0.259	0.095
Rth Sample 4E	0.344	0.855	0.582	0.969	2.181	4.447	4.752	4.934	1.036	1.027	0.256	0.134
stdev Rth	0.008	0.020	0.016	0.034	0.069	0.095	0.098	0.122	0.028	0.101	0.016	0.022
median Rth	0.341	0.851	0.565	0.898	2.134	4.299	4.585	4.664	0.990	1.017	0.255	0.120
stdev Rth/median Rth	2.4%	2.4%	2.8%	3.8%	3.2%	2.2%	2.1%	2.6%	2.9%	10.0%	6.2%	18.7%

level 2 package. Correlation coefficients equal to or larger to 0.75 are depicted in green. The sum of all correlation coefficients tells us which stages are on average the most correlated to all the other stages. Stage 7 is the most correlated (body + pads and solder + top of the MCPCB circuit), followed closely by stage 9 (MCPCB core) and stage 6 (bottom of the copper layer). The first three stages are all strongly correlated to one another, which makes completely sense as they all belong to the chip stack. Among them stage one is the most correlated to the 2 others.

Table 2: RB Correlation coefficient matrix for stages 1 to 12. Correlation coefficients ≥ 0.75 are reported in green.

Stage#	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10	Stage 11	Stage 12	Σcorcoeff	Corresponding physical layers
Stage 1	1.00	1.00	0.88	0.54	0.68	0.57	0.67	0.29	0.52	-0.28	-0.21	0.42	6.06	top chip stack
Stage 2	1.00	1.00	0.85	0.48	0.67	0.52	0.62	0.22	0.49	-0.28	-0.23	0.40	5.72	middle chip stack
Stage 3	0.88	0.85	1.00	0.40	0.57	0.47	0.61	0.42	0.45	-0.44	-0.21	0.11	5.12	middle chip stack
Stage 4	0.54	0.48	0.40	1.00	0.47	0.80	0.88	0.62	0.58	0.10	0.13	0.65	6.64	bottom chip stack
Stage 5	0.68	0.67	0.57	0.47	1.00	0.74	0.68	0.49	0.75	0.16	0.17	0.38	6.75	voided die attach + top cu layer
Stage 6	0.57	0.52	0.47	0.80	0.74	1.00	0.95	0.69	0.83	0.18	0.28	0.43	7.46	bottom cu layer
Stage 7	0.67	0.62	0.61	0.88	0.68	0.95	1.00	0.68	0.77	0.04	0.17	0.47	7.55	body + pads and solder + top mcpcb circuit
Stage 8	0.29	0.22	0.42	0.62	0.49	0.69	0.68	1.00	0.76	0.28	0.49	0.23	6.17	bottom mcpcb circuit + mcpcb dielectric + top mcpcb core
Stage 9	0.52	0.49	0.45	0.58	0.75	0.83	0.77	0.76	1.00	0.48	0.35	0.52	7.49	mcpcb core
Stage 10	-0.28	-0.28	-0.44	0.10	0.16	0.18	0.04	0.28	0.48	1.00	0.60	0.45	2.28	dry die attach + top coldplate
Stage 11	-0.21	-0.23	-0.21	0.13	0.17	0.28	0.17	0.49	0.35	0.60	1.00	-0.15	2.39	middle coldplate
Stage 12	0.42	0.40	0.11	0.65	0.38	0.43	0.47	0.23	0.52	0.45	-0.15	1.00	4.91	bottom coldplate

In Figure 5, an identical approach to the methodology used for RB in Figure 3 is applied to consider variability of PCW LEDs, by segmenting once again C_{th} range in 12 segments of similar standard deviation (dotted line, values reported on y-axis right). It is noteworthy that despite having discarded the sample with delamination, fluctuation peaks are located at the same positions but are consistently larger for the PCW LEDs.

Table 3 lists C_{th} values for all 12 stages as well as corresponding R_{th} values for all 10 samples.

Absolute Stdev is the largest for stage 5 (voided die attach + top of copper layer), 6 (bottom of copper layer), 10 (dry die attach + top of cold plate), 7 (body + pads and solder + top of MCPCB circuit) and 8 (bottom of MCPCB circuit + dielectric + top of MCPCB core). It is the lowest for the chip stack (stages 1 to 4) and the cold plate (stages 11 and 12). Relative Stdev is the largest for stages 10, 11 and 12, corresponding to the cold plate.

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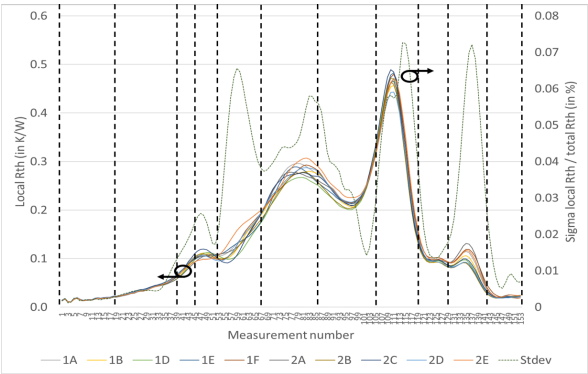

Figure 5: 10 PCW samples Local R_{th} (y-axis left, full lines) vs C_{th} and σ Local R_{th} / total R_{th} (y-axis right, dotted line) vs C_{th}. 12 C_{th} stages are defined based on areas of equivalent fluctuation.

Table 3: PCW 12 stages RC ladder average C_{th} and individual samples R_{th} for the 11 PCW samples.

	stage 1	stage 2	stage 3	stage 4	stage 5	stage 6	stage 7	stage 8	stage 9	stage 10	stage 11	stage 12
average Cth (11 samples)	8.9E-06	3.3E-05	4.7E-05	4.1E-05	1.7E-04	5.9E-04	5.3E-03	3.0E-02	1.3E-01	1.2E+00	1.1E+01	3.9E+01
Rth sample 1A	0.303	0.759	0.480	0.851	2.114	4.838	4.872	4.772	1.045	1.194	0.285	0.133
Rth sample 1B	0.291	0.727	0.453	0.863	2.029	4.608	4.831	4.645	1.006	1.100	0.258	0.140
Rth sample 1D	0.288	0.721	0.439	0.862	1.855	4.396	4.640	4.695	1.006	1.032	0.266	0.137
Rth sample 1E	0.308	0.775	0.484	0.833	2.046	4.652	4.811	4.861	1.043	0.983	0.272	0.127
Rth sample 1F	0.294	0.736	0.471	0.827	2.094	4.667	4.930	4.882	1.109	1.278	0.296	0.159
Rth sample 2A	0.284	0.712	0.428	0.828	2.063	4.673	4.807	4.700	1.036	1.335	0.304	0.150
Rth sample 2B	0.300	0.748	0.483	0.850	1.982	4.489	4.689	4.628	0.988	0.966	0.255	0.125
Rth sample 2C	0.308	0.766	0.488	0.911	1.924	4.678	4.891	4.849	1.040	1.059	0.266	0.143
Rth sample 2D	0.299	0.748	0.481	0.825	2.072	4.688	4.909	4.572	1.033	0.995	0.253	0.143
Rth sample 2E	0.292	0.736	0.462	0.787	2.374	4.831	5.056	4.881	1.104	1.224	0.300	0.127
stdev Rth	0.008	0.020	0.021	0.032	0.138	0.135	0.119	0.115	0.039	0.132	0.019	0.011
median Rth	0.297	0.742	0.475	0.841	2.055	4.670	4.852	4.736	1.038	1.080	0.269	0.138
stdev Rth/median Rth	2.8%	2.7%	4.4%	3.8%	6.7%	2.9%	2.5%	2.4%	3.8%	12.2%	7.1%	7.8%

Table 4 below compiles the correlation coefficients matrix for R_{th} distributions of stages 1 to 12 as well as corresponding physical layers of the RB level 2 package.

The sum of all correlation coefficients tells us which stages are on average the most correlated to all the other stages. Stage 6 is the most correlated, followed closely by stage 7 and 9. The first three stages are all strongly correlated to one another, which makes completely sense as they all belong to the chip stack. Among them stage 1 is the most correlated to the 2 others. Stages 10 and 11 are also strongly correlated, as they belong to the cold plate and its interface with the LED package.

Table 4: PCW Correlation coefficient matrix for stages 1 to 12. Correlation coefficients ≥ 0.75 are reported in green.

Stage#	stage 1	stage 2	stage 3	stage 4	stage 5	stage 6	stage 7	stage 8	stage 9	stage 10	stage 11	stage 12	Zcorcoeff	Corresponding physical layers
stage 1	1.00	0.99	0.91	0.36	-0.10	0.25	0.14	0.30	-0.01	-0.54	-0.39	-0.35	2.59	Phosphor+Silicone + Top chip stack
stage 2	0.99	1.00	0.91	0.26	-0.02	0.30	0.18	0.35	0.05	-0.51	-0.31	-0.39	2.81	middle chip stack
stage 3	0.91	0.91	1.00	0.20	0.04	0.27	0.26	0.21	0.09	-0.51	-0.40	-0.29	2.72	middle chip stack
stage 4	0.36	0.26	0.20	1.00	-0.80	-0.38	-0.44	-0.11	-0.53	-0.38	-0.52	0.11	-1.21	bottom chip stack
stage 5	-0.10	-0.02	0.04	-0.80	1.00	0.78	0.83	0.37	0.71	0.50	0.59	-0.16	3.73	voided die attach + top cu layer
stage 6	0.25	0.30	0.27	-0.38	0.78	1.00	0.87	0.45	0.66	0.51	0.53	0.03	5.27	bottom cu layer
stage 7	0.14	0.18	0.26	-0.44	0.83	0.87	1.00	0.50	0.82	0.46	0.46	0.18	5.25	body + pads and solder + top mcpcb circuit
stage 8	0.30	0.35	0.21	-0.11	0.37	0.45	0.50	1.00	0.76	0.38	0.61	0.04	4.87	bottom mcpcb circuit + mcpcb dielectric + top mcpcb core
stage 9	-0.01	0.05	0.09	-0.53	0.71	0.66	0.82	0.76	1.00	0.62	0.74	0.33	5.25	mcpcb core
stage 10	-0.54	-0.51	-0.51	-0.38	0.50	0.51	0.46	0.38	0.62	1.00	0.91	0.54	2.99	dry die attach + top cold plate
stage 11	-0.39	-0.31	-0.40	-0.52	0.59	0.53	0.46	0.61	0.74	0.91	1.00	0.30	3.52	middle cold plate
stage 12	-0.35	-0.39	-0.29	0.11	-0.16	0.03	0.18	0.04	0.33	0.54	0.30	1.00	1.33	bottom cold plate

Method 2: Statistical model fitting measurement

This method uses splines (piecewise polynomials with smooth connections at the connecting knots) to model the data of the structure functions [6].

For each sample, a B-spline with degree 3 was fitted with cumulative C_{th} values as predictor (on log scale) and R_{th} as response. The knots of the splines were preselected using a combination of the physical layers and inflection points that were manually chosen after visual inspection of data plots that were smoothed using local regression (loess) therefore providing better C_{th} granularity than for Method 1 (all measurements points are considered using this statistical model, and not 12 stages solely). Figure 6 presents the data (shown as black dots) and the B-spline regression of an RB sample (shown as a red line) while Figure 7 presents the B-spline regression of a PWC sample.

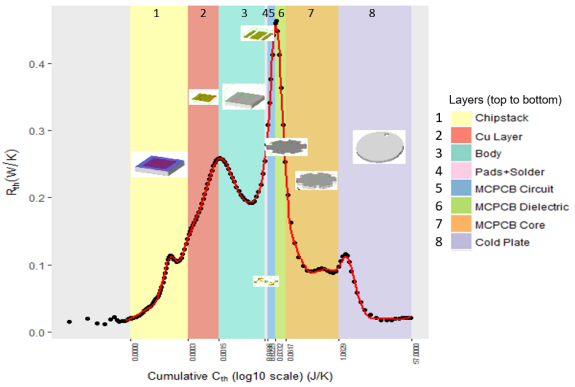

Figure 6: RB LED sample 3A – Regression line of method 2 on Local R_{th} vs cumulative C_th.

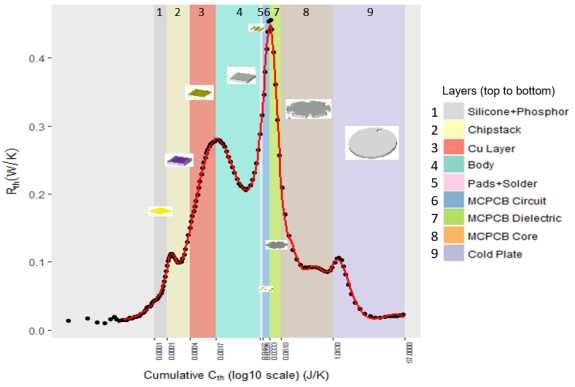

Figure 7: PCW LED sample 1B – Regression line of method 2 on Local R_{th} vs cumulative C_th.

The spline basis was reduced by discarding non-significant basis elements. Normal distributions were fitted to the individual spline

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basis coefficients by combing the samples. Since the samples were small and thus outliers may have bias the results, robust estimators for the mean (median) and variance (Mean Absolute Deviation [7]) were used.

Random structure functions were generated by drawing random samples from the distribution of each spline basis coefficient and then summing them up to obtain a spline representation of a random structure function. This approach was applied separately to the RB and PCW samples.

Monte Carlo Simulations and Results

Purpose of these Monte Carlo simulations is to deliver large enough thermal input distributions matching measured thermal fluctuations required by the multi domain model so that influence of thermal variability can be implemented in electrical and photometric modeling.

Method 1: from RC ladder and correlation coefficients

For the RB LEDs, Monte Carlo draws are done as follows:

- Stage 1 Monte Carlo generated samples are drawn following its normal distribution as it is the most correlated to stage 2 and 3 (all belonging to chip stack).
- Stages 2 and 3 all have correlation coefficients ≥ 0.75 versus stage 1, so stage 2 and 3 generated samples are simply calculated from stage 1 drawn values according to the root mean square slope between stage 1 and stage 2 and between stage 1 and stage 3.
- Stage 7 MC generated samples are drawn following its normal distribution as it is the stage the most correlated to all the other ones. Stages 4, 6 and 9 all have correlation coefficients ≥ 0.75 versus stage 7, so stages 4, 6 and 9 generated samples are simply calculated from stage 7 drawn values according to the root mean square slope between stage 7 and stage 6, stage 7 and stage 6 and between stage 7 and stage 9.
- For all the other stages: 5, 8, 10, 11, 12, independent Monte Carlo generated samples are drawn following their respective normal distributions, like it is done for stages 1 and 7. The resulting 1000 RC ladders with 12 stages are depicted in Figure 8 below.

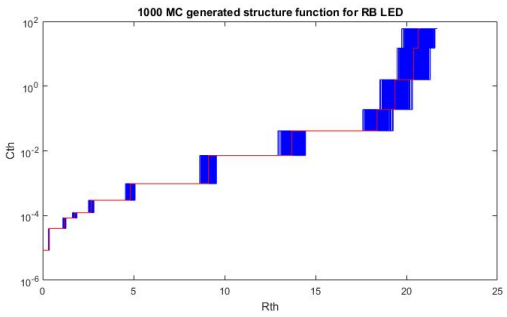

Figure 8: RB 1000 Monte Carlo generated RC ladder structure functions (blue). Median among the 1000 samples (red).

For the PCW LEDs, Monte Carlo draws are done as follows:

- Stage 1 Monte Carlo generated samples are drawn following its normal distribution as it is the most correlated to stage 2 and 3 (all belonging to chip stack).
- Stages 2 and 3 all have correlation coefficients ≥ 0.75 versus stage 1, so stage 2 and 3 generated samples are simply calculated from stage 1 drawn values according to the root mean square slope between stage 1 and stage 2 and between stage 1 and stage 3.
- Stage 7 MC generated samples are drawn following its normal distribution as it is after stage 6 the most correlated to all the other ones while having among stages 5, 6 and 7 the largest correlation coefficients with the two others. Stages 5, 6 all have correlation coefficients ≥ 0.75 versus stage 7, so their samples are simply calculated from stage 7 drawn values according to the root mean square slope between stages 7 and 6 and between stages 7 and 5.
- Stage 9 is drawn following its normal distribution. Its correlation coefficient against stage 8 being ≥ 0.75 (and the sum of all correlation coefficients for stage 9 being larger than the sum for stage 8), samples for stage 8 are calculated using the root mean square slope between stages 9 and 8.
- In a similar fashion, stage 11 is drawn independently while stage 10 is deduced from the root mean square slope against stage 11.
- Lastly, stages 4 and 12 being poorly

correlated to other stages, independent draws are made for these two.

The resulting 1000 RC ladders with 12 stages are depicted in Figure 9 below.

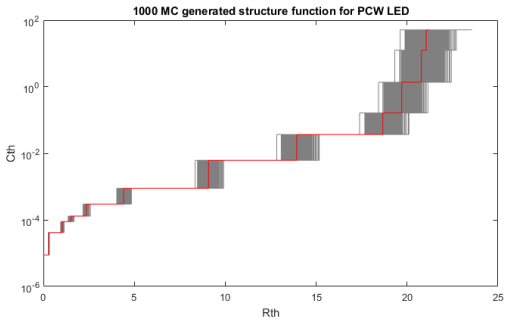

Figure 9: PCW 1000 Monte Carlo generated RC ladder structure functions (blue). Median among the 1000 samples (red).

The 1000 structure functions are then processed in a solver in order to get back thermal transient change curves (from t = 0 to 600 seconds) in a computation process which is the opposite to the one described in the Appendix. Those are depicted in Figure 10 and Figure 11 below for RB and PCW respectively and for a power dissipation of 1 watt.

For each of the 12 stages, 1000 thermal transient change curves are depicted. Temperature rise at 600 seconds is the one of stage 12, stage 12 representing the chip junction where the 1 watt power is dissipated. RB LEDs max temperature stabilized earlier than for PCW.

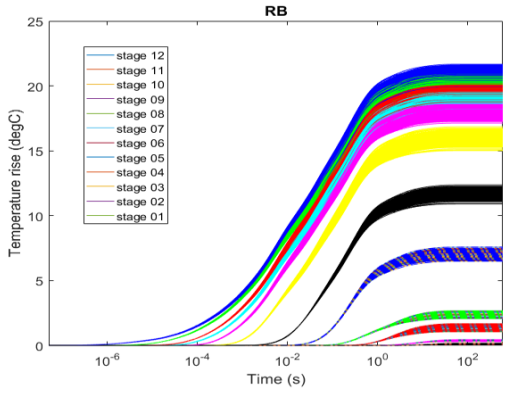

Figure 10: RB 1000 Monte Carlo generated thermal transient change curves for the 12 RC ladder stages.

Figure 12 is the distribution of 1000 samples maximum Temperature rise at 600 seconds for both RB and PCW.

For RB, mean is equal to 20.76 °C, stdev is equal

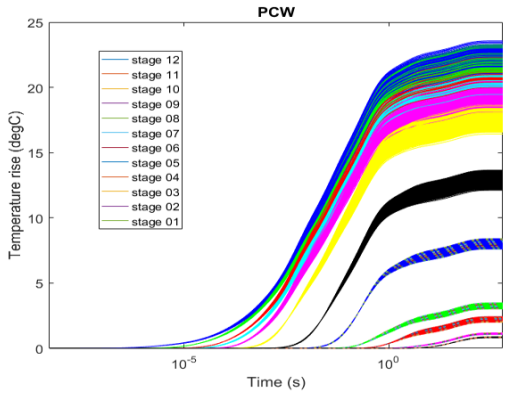

Figure 11: PCW 1000 Monte Carlo generated thermal transient change curves for the 12 RC ladder stages.

to $\pm$0.30 °C, and 3σ/mean relative variation is $\pm$4.39%.

For PCW, mean is 21.89 °C, stdev is $\pm$0.46 °C and 3σ/mean relative fluctuation represents $\pm$6.36%.

PCW temperature rise is 1.13 °C larger than RB, while relative fluctuation is also larger for PCW. This correlates qualitatively with the steady state temperature variance observed from measurement as seen in Figures 1 and 2. This could be explained by the presence of phosphor. Extra layer of silicone + phosphor is an additive heat source due to photon energy conversion (Stoke shift). The increase in overall thermal resistance of the PCW is attributed to this additional power being dissipated in the silicone+phosphor deposited layer that has a much lower thermal conductivity compared to the GaN LED junction. The variance of this increased thermal resistance could be attributed to variations in the phosphor by volume distribution in this deposited layer.

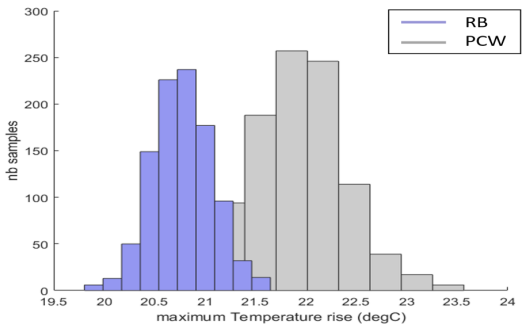

Figure 12: For both RB and PCW, distribution for the 1000 samples of maximum rising temperature at 600 seconds for stage 12.

Standard deviation of temperature rise as a

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function of time for the 1000 samples of RB and PCW are shown in Figure 13 (top) below. Relative fluctuation (σTemperature/mean Temperature at each time, in %) is reported in Figure 13 (bottom) for both RB and PCW. As one can see, both sets of LEDs temperature fluctuation profile are similar, showing a sudden rise near 1 µs, but beyond this time, PCW temperature rise fluctuates more, especially after 10 ms. This corresponds with the thermal time constant of the silicone+phosphor deposit layer.

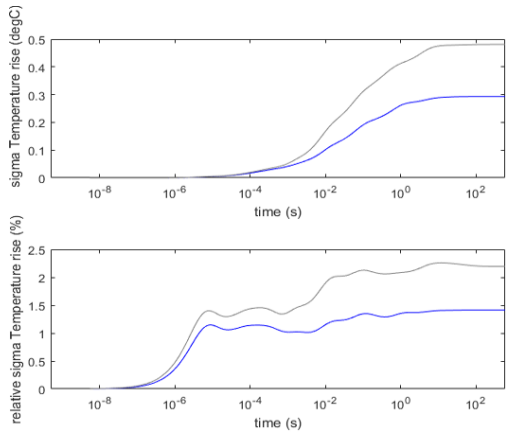

Figure 13: Standard deviation (top) and relative fluctuation (σ/median) (bottom) for the 1000 samples of thermal transient change for stage 12 of the RC ladder for RB (blue) and PCW (grey) LEDs.

Method 2: from statistical model fitting measurement

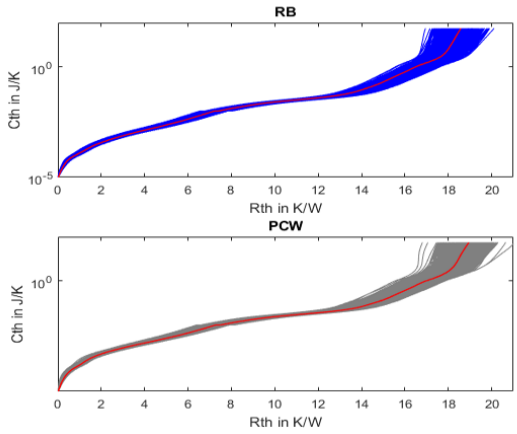

Figure 14: The 1000 Monte-Carlo generated structure functions (blue) using method 2 for RB (top) and PCW (bottom). Median is also plotted (red).

Set of 1000 Structure functions generated using method 2 are depicted in Figure 14 for RB and PCW.

As expected, overall R_{thJA} spread is larger for PCW than for RB.

Transient temperature change curves obtained using the same solver as for Method 1 (but this time at each individual C_{th} measurement point) are depicted in Figure 15 for RB and PCW 1000 samples.

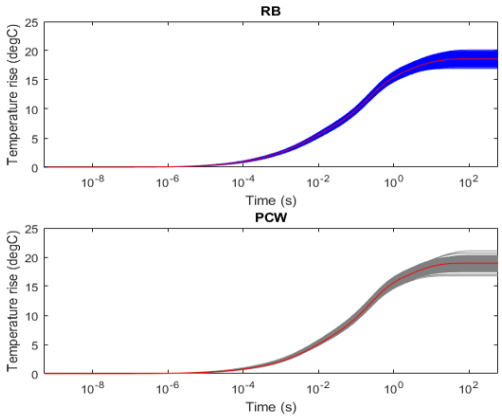

Figure 15: The 1000 transient rising temperature curves generated using method 2 for RB (blue, top) and PCW (grey, bottom). Median is also plotted (red).

Figure 16 shows distributions of maximum temperature rise at 600 seconds for both sets of LEDs using method 2.

For RB, mean is equal to 18.57 °C while stdev is equal to ±0.48 °C. 3σ/mean relative fluctuation is ±7.82%

For PCW, mean is equal to 18.96 °C while stdev is ±0.54 °C. 3σ/mean relative fluctuation is ±8.62%.

As for method 1, maximum temperature rise is larger for PCW compared to RB, but only by 0.42 °C this time. Also, fluctuation is also this time larger for PCW, but again to a smaller extent compared to method 1.

Figure 17 (top) depicts the standard deviation of temperature rise as a function of time. PCW absolute standard deviation is systematically slightly larger than for RB, especially beyond 30 seconds.

Relative fluctuation (σ Temperature/mean Temperature at each time, in %) is reported in Figure 17 (bottom) for both RB and PCW for method 2. While relative fluctuation rises as of 1 µs as for method 1 for both LED types, profile beyond 10 µs is strikingly different as

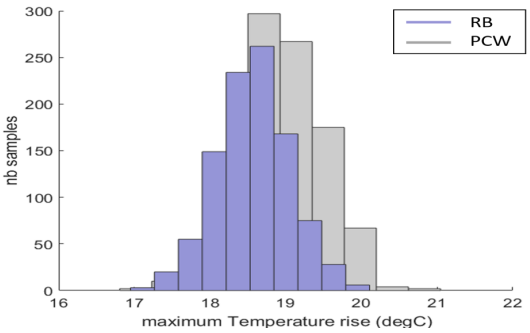

Figure 16: For both RB and PCW, distribution for the 1000 samples of maximum rising temperature at 600 seconds using method 2.

it drops and then stabilizes. Nevertheless, PCW relative fluctuation is once again systematically larger than RB, though largest difference is found at 10 µs (5.2% for RB and 8.0% for PCW). While method 1 segments structure functions in 12 stages, method 2 considers each individual measurement point to fit curves using splines and loess local regression. On the other hand, method 1 considers correlation coefficients in variation of R_{th} between stages while method 2 doesn't. The better comparison between measurement and the Monte Carlo method 1, in terms of magnitude and variance of steady state thermal resistance, indicates the need to consider inter-stage correlations when constructing the RC CTM ladder model.

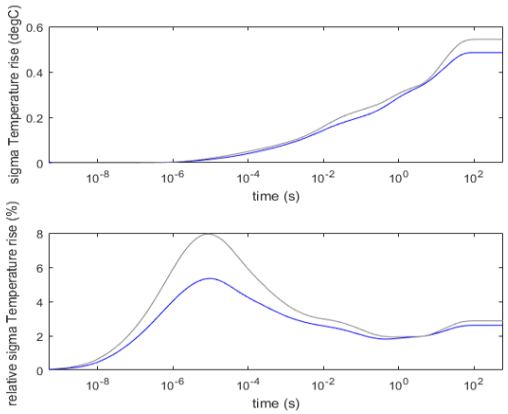

Figure 17: For both RB (blue) and PCW (grey), σ (top) and relative σ (σ/median) (bottom) of 1000 transient rising temperature curves using method 2.

As shown in Figure 18, having mean and standard deviation estimate on rising temperature (and deduced Junction Temperature) from the Compact Thermal Model will allow to feed the Multi-Domain Model computing electrical and optical characteristics. In return, and in auto-coherent way from the Multi-Domain Model computed thermal dissipation mean and standard deviation will be used as an input by the Compact Thermal Model triggering dynamic thermal information exchange influencing LED package performance. This will be the topic of a future publication within Delphi4LED.

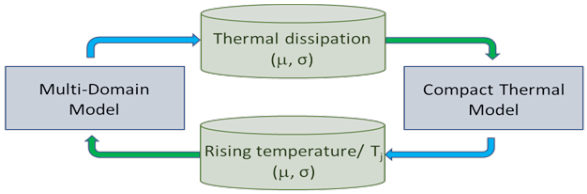

Figure 18: Diagram showing auto-coherent Compact Thermal Model and Multi-Domain Model echange of thermal information.

Electrical and Optical Measurements

Electrical, radiometric and photometric characteristics for 11 level 2 samples with RB LEDs and for 10 level 2 samples with PCW LEDs were measured following the measurement cartography depicted in Table 5 below.

Measurement conditions were as follows:

- For every LED, a preliminary burn in measurement of 500 hours duration at nominal current and 85 °C Air/Cold plate temperature in an isothermal chamber was performed. Purpose of this preliminary conditioning was to age LEDs long enough to be able to measure stable performance of LED packages in a more realistic use condition.
- To obtain electrical and optical characteristics, LEDs were measured using continuous currents and reported junction temperature (T_j) were targeted using a V_f based T_j regulation methodology [8].

In the present paper, only measured electrical and optical characteristics and their fluctuations are listed. Modeling of fluctuation will be the topic of a future paper in Delphi4LED.

Electrical Characteristics

Forward voltage was characterized as a function of forward current according to the measurement cartography reported in Table 5.

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Table 5: (I_f, T_j) **cartography used for electrical, radiometric and photometric measurements for RB and PCW LEDs.**

IVL characteristics		TJ [°C]				
		30	50	70	85	110
IF [mA]	20	RB/PCW	RB/PCW	RB/PCW	RB/PCW	.
	30	RB/PCW	RB/PCW	RB/PCW	RB/PCW	.
	60	RB/PCW	RB/PCW	RB/PCW	RB/PCW	.
	100	RB/PCW	RB/PCW	RB/PCW	RB/PCW	.
	350	RB/PCW	RB/PCW	RB/PCW	RB/PCW	.
	500	RB	RB/PCW	RB/PCW	RB/PCW	PCW
	700	.	RB/PCW	RB/PCW	RB/PCW	RB/PCW
	1000	.	.	RB/PCW	RB/PCW	RB/PCW

Relative fluctuation of measured forward voltage is calculated using Formula (1).

$$V_f \text{ fluctuation} = \frac{\sigma(V_f)}{\text{median}\,(V_f)} \cdot 100 \qquad (1)$$

Relative fluctuation is plotted as a function of forward current in Figure 19 (right). Fluctuation is small (smaller than 1.3%). It is increasing with forward current and is ≈ 30% larger for PCW LEDs compared than for RB LEDs. No hard conclusion can be derived from such a difference, but the root cause can likely be found among the followings:

- LED manufacturing batches/wafers for the two sets are necessarily different, so diodes are likely different.
- It is known that binning processes for RB and PCW are not based on same criteria (min/max luminous flux at 350 mA and 85 °C for PCW and min radflux at 350 mA and 25 °C and min/max peak wavelength for RB).
- Phosphor deposition process could also lead to some additive variability: phosphor acts as a heat source because of the energy released by the photons energy conversion from blue to white [9].

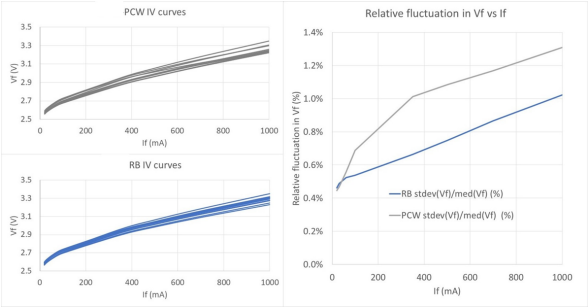

Figure 19: **IV characteristics for PCW (top left) and RB (bottom left) samples at 85 °C T_j. Relative V_f fluctuation (in %) as a function of I_f (right).**

Optical Characteristics

Radiant flux as a function of forward current for the 10 PCW and the 11 RB samples, measured at 85 °C are depicted in Figure 20. As expected, Radflux is increasing more as a function of I_f for the RB LEDs as phosphor absorption and fully isotropic re-emission lowers measured flux in the integration sphere. Radflux is consequently more than 1.5 times larger at 1000 mA for the RB LEDs.

Radflux relative fluctuation shown in Figure 20 (right) is calculated using Formula (2).

$$\text{Radflux fluctuation} = \frac{\sigma(\text{Radflux})}{\text{median(Radflux)}} \cdot 100 \qquad (2)$$

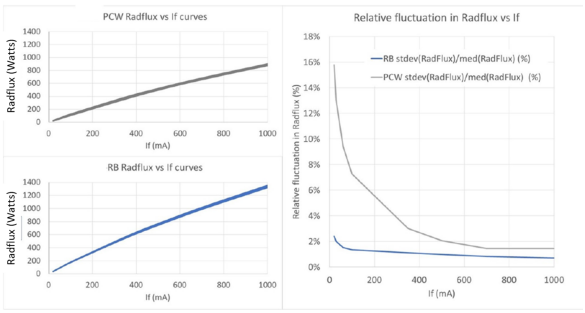

Figure 20: **Radflux vs If characteristics for PCW (top left) and RB (bottom left) samples at 85 °C T_j. Relative Radflux fluctuation (in %) as a function of If (right).**

Relative Radiant flux fluctuation drops with forward current for both RB and PCW LEDs. As leakage is dominant in the low current region, one can conclude it is leakage which is responsible for this larger relative fluctuation. Also noteworthy to state is that PCW LEDs relative fluctuation is significantly larger at low current than for RB (6.4 times larger at 20 mA). Once again, it is not obvious to draw hard conclusions from such a result. Leakage possibly has a role here as well as the deposition of phosphor and its role in the photons conversion for the PCW LED. But once again, binning criteria are different and LED batches/wafers are also completely different in both cases. Such a result would deserve more statistics on some other samples before being able to conclude on root cause. These electrical and photometric measurement results and their fluctuations will be used as an input, together with the thermal Monte Carlo results on modeled temperature rise presented in section *IV* in a future work for the modeling of fluctuation using the $I - V - L$ multi domain model.

Normalized Spectral Power Distributions (SPDs) measured at I_f of 700 mA and 85 °C for both set of

LEDs are plotted in Figure 21. For the binned PCW, CCT median is 5162K, 3σ is $\pm$133. Looking at colorimetry perception indexes, CRI median is 70.3, 3σ is $\pm$1.8. TM-30 Rf (TM-30 fidelity index, comparable to CRI) is 68.7, 3σ is $\pm$3.6. For circadian indexes, calculated for an illuminance of a typical indoor luminaire of 250 Lux, EML (Equivalent Melanopic Lux) median is 174.0 Lux, 3σ is $\pm$7.9 Lux, Cs (Circadian index) median is 0.25, 3σ is $\pm$0.02.

For horticulture indexes, PPF (Photosynthetic Photon Flux) median is 0.0134 µmol s^{-1} Lum^{-1}, 3σ is $\pm$0.004 µmol s^{-1} Lum^{-1}. PPFD (Photosynthetic Photon Flux Density) median, also calculated at an illuminance of 250 Lux, is equal to 3.35 µmol s^{-1} m^{-2}, 3σ is 0.10 µmol s^{-1} m^{-2}. Finally, PSS (Phytochrome Photostationary State) median is 0.83, and 3σ is 0.01.

Some more insight on the implication of binning on colorimetry and cicradian indexes at luminaire level can be found in [10].

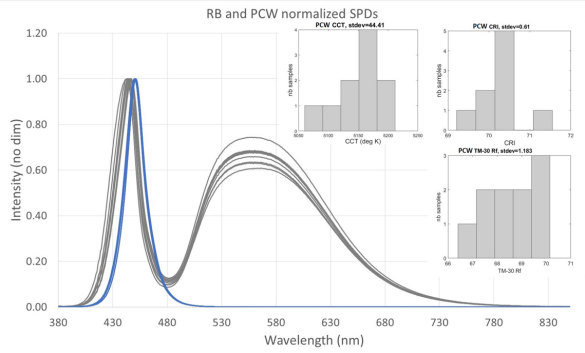

Figure 21: SPDs of the 11 RB (blue) and 10 PCW (grey) LEDs. Normalized intensity (x) vs Wavelength (y) at 700 mA forward current and 85 °C T_j. PCW LEDs distributions in CCT, CRI and TM-30 Rf in top right corner.

Conclusions

Aim of this work was to propose for the first time a methodology to model how LED packages can vary thermally from one sample to another. Careful thermal, optical and electrical measurements on 11 Royal blue LED packages and 10 Phosphor converted white LED package (same royal blue chip, but with phosphor on top) were conducted.

Protocol to perform a thermal transient measurement and to translate it into a structure function has been briefly described.

A statistical analysis on this limited pool of measured LED packages has been conducted. Then, a Monte-Carlo approach has been defined in order obtain a realistic and large amount (1000) of thermal structure functions.

Two methods were employed: first one by segmenting structure functions in a 12 stages RC ladder, all representing areas of equivalent fluctuation. Monte-Carlo generation also took in consideration correlation in variation between stages. Second method uses advanced splines fitting together with smoothening using local regression (loess), taking this time all measurements points in consideration. Monte-Carlo samples are generated looking at the splines model parameters and their distributions.

Using both methods, a larger temperature rise of about 1 °C pet watt of thermal power was found for the phosphor converted white LEDs compared to their royal blue counterparts. Both methods also led to similar conclusion on variation: PCW LED temperature fluctuates 45% more using method 1 ($\pm$0.90 °C at 3σ for RB, $\pm$1.38 °C at 3σ for PCW) and 10% more using method 2 ($\pm$1.46 °C at 3σ for RB, $\pm$1.62 °C at 3σ for PCW).

Electrical (IV) and optical measurement (Radiant Flux, SPDs) variation were also quantified. These results will be used as an input for future work using the multi domain model within Delphi4LED which requires temperature input for electrical and optical modeling.

Also, for the PCW LED, variability implication on metrics such as CCT (median 5162 K, $3\sigma \pm 133$ K) were quantified. This was also done for colorimetry perception indexes such as CRI (median 70.3, $3\sigma \pm 1.8$) and TM-30 Rf (median 68.7, $3\sigma \pm 3.6$) but also circadian and horticulture perception indexes such as EML (median 174 Lux, $3\sigma \pm 7.9$ Lux), Cs, PPF, PPFD and PSS.

From Thermal Transient to Structure Functions

Per LED, a V_f vs T_j calibration curve needs to be generated in order to be able to translate measured voltage changes in temperature changes later on. An example for such a calibration curve can be found in Figure 22 below. These data are required for the next steps in order to translate V_f changes into Temperature changes. It is normally done using the slope of a

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simple linear fit (the so called *k*-factor). It will be demonstrated later on that a quadratic interpolation leads to more reliable results.

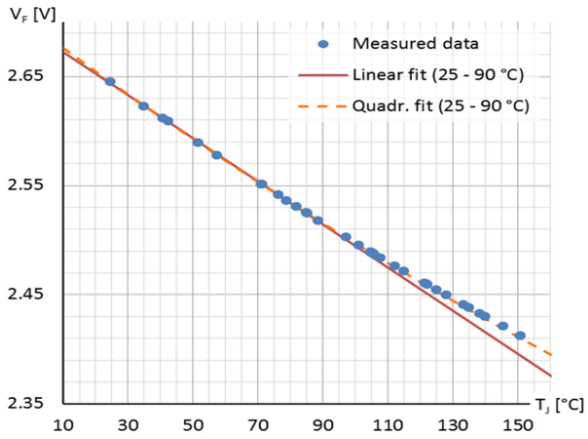

Figure 22: V_f **vs** T_j **calibration curve for a Royal Blue LED. Both linear and quadratic fits in the 10 to 90 °C range are depicted.**

In Figure 23, thermal transient change curve, obtained from V_f change curve at I_f = 700 mA is shown. Two set of curves are depicted: the one using a linear calibration and the one using a quadratic calibration. Accordingly, "hot" points displayed at 1 µs time on left side of the chart seem to be fallaciously nearer to the T_j setpoint using the linear calibration set — although the physically reached hot T_j value is rather the one belonging to the curves with quadratic calibration.

Right end of the curves after one minute of cooling corresponds to the programmed T_{cp} value. The figure proves that targeted T_J value was reached with ∼ 2 °C accuracy within the actual calibration range, 10–90 °C.

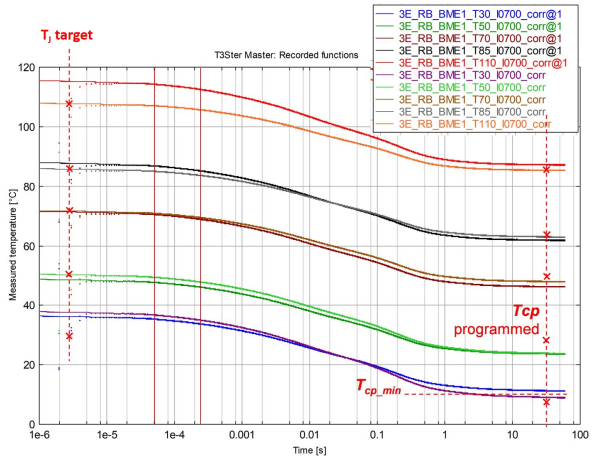

Figure 23: Temperature change curve of Royal Blue LED obtained from V_f **change curve (at 700 mA** I_f**, *corr curves with linear, *corr@1 curves with quadratic calibration.**

The first evident step of generalizing temperature measurement result can be done normalizing it by the applied power. This normalized temperature transient is the Z_{th} curve (not shown here) also known as thermal impedance curve.

In the world of silicon (single energy transport) devices all input electric energy is converted into heating power:

$$P_H = P_{el} \tag{3}$$

$$\text{thus: } Z_{th}(t) = \frac{T_J(t)}{\Delta P_{el}} \tag{4}$$

As depicted in Figure 24, from Z_{th} curves measured on a T3STER setup [11] at 85 °C T_j and at forward currents of 100, 350, 500, 700 and 1000 mA, structure function curves (SF) are obtained using a C_{th} and R_{th} equivalent circuit compact model. In more details, thermal impedance curve is fist numerically derived, then a numerical deconvolution is applied to obtain a time constant spectrum. This spectrum is discretized and fitted using a Forster model of the impedance. Lastly, a transformation is applied using a Cauer model of the impedance used to obtain the structure function.

Interest of structure function is to analyze layers constituting the level 2 package (chip – package – glue – starboard compound).

Perfection of the quadratic calibration approach is verified in Figure 24. The chart displays the structure functions of the packaged LED with starboard mounting, at the same T_J = 85 °C junction temperature but in a broad powering range. Applied forward current grew from 100 mA to 1 A in five steps. Structure functions completely fit, without artificial tampering.

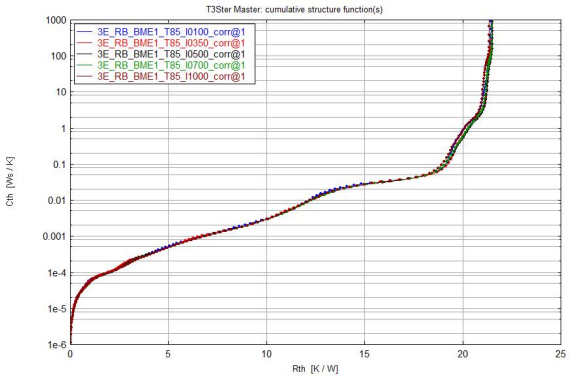

Figure 24: Structure functions of the royal blue power LED with quadratic calibration, T_J = 85 °C, I_f **from 100 mA to 1000 mA.**

Acknowledgment

Contribution of European Union for supporting this work in the context of H2020 ECSEL Joint Undertaking program (2016–2019) within the frames of the Delphi4LED project (grant agreement 692465) is acknowledged. Delphi4LED project co-financing by Research and Development funding organizations of governments of countries participating in this experiment through their national grant agreements is also acknowledged.

References

[1] www.Delphi4LED.org

[2] A. Poppe, “From Measurements to Standardized Multi-Domain Compact Models of LEDs: Towards predictive and efficient modeling and simulation of LEDs at all integration levels along the SSL supply chain”, In: R. Devonshire, G. Zissis, Y. Kawakami, M. Jinno, T. Yasuda (eds.), “Proceedings of the 15th International Symposium on the Science and Technology of Lighting (LS15)” 22–27 May 2016, Kyoto, Japan, pp. 387–392.

[3] R. Bornoff et al., “Delphi4LED – From Measurements to Standardized Multi-Domain Compact Models of LEDs: a New European Research and development Project for Predictive and Efficient Multi-domain Modeling and Simulation of LEDs at all Integration Levels Along the SSL Supply Chain”, In: Proc. of 22nd THERMINIC, Sep. 2016, Budapest, Hungary, DOI: 10.1109/THERMINIC.2016.7749048.

[4] J.K. Sari et al., “Delphi4led: LED measurements and variability analysis”, Proc. of 23rd THERMINIC, Sep. 2017, Amsterdam, The Netherlands, DOI: 10.1109/THERMINIC.2017.8233797.

[5] R. Bornoff et al., “Quantified Insights into LED Variability”, to be published in Proc. of 24th THERMINIC, Sep. 2018, Stockholm, Sweden.

[6] C. de Boor (2001). A Practical Guide to Splines (revised edition). Springer.

[7] D.C. Hoaglin, F. Mosteller and J.W. Tukey. Understanding Robust and Exploratory Data Analysis. Wiley, New York, 1983.

[8] M. C. Bein, “Comparison of Two Alternative Junction Temperature Setting Methods Aimed for Thermal and Optical Testing of High Power LEDs”, Proc. of 23rd THERMINIC, Sep. 2017, Amsterdam, The Netherlands, DOI: 10.1109/THERMINIC.2017.8233838.

[9] Gispert, J. R. (2008). Coordination Chemistry. Wiley-VCH. p. 483. ISBN 3-527-31802-X.

[10] T. Mérelle et al., “A methodology to assess the impact of LED process variability on colorimetry”, Proc. of the 7th LED Professional Symposium, Sept 26–28 2017.

[11] https://www.mentor.com/products/mechanical/micred/t3ster/

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Hermetic Polymer-Free White LEDs for Harsh Environments

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Abstract

White LEDs can achieve lifetimes of several 10 000 h depending on junction temperature and current density. However, state of the art polymer-encapsulated LEDs with powder-based phosphors reveal a strong dependence of field lifetimes on environmental conditions such as humidity, corrosive gas and air pollutant exposure. An interesting alternative to polymer-dispersed phosphors are luminescent ceramics. The development of such ceramic phosphor wafers for LED conversion with diameters of up to 100 mm is demonstrated. They can be manufactured impermeable, provide a 30 times higher thermal conductivity and are chemical, mechanical and temperature resistant. To facilitate this Fraunhofer has developed high-power LEDs which use luminescent ceramics as hermetic, light converting cap material. Since pollutants cannot penetrate inside and give rise to corrosion, a direct application of these new LEDs without elaborate external housing in chemical burdened environments is possible. As a further advantage the inevitable heat generated by the light conversion is dissipated through the thermally conductive ceramics itself, rather than further burdening the LED chip. This allows high ambient temperature operation. Furthermore, the developed wafer-level package technology allows long device lifetimes with low color drift by completely avoiding polymers.

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Introduction

Thermal issues

During the last years phosphor conversion white light emitting diodes (LEDs) based on the AlGaInN-thin-films [1] have replaced traditional light sources in most lighting applications with market shares of up to 80%. Under optimal conditions these white LEDs can achieve lifetimes of up to 100 000 h [2] depending on junction temperature and current density. However state of the art silicone encapsulated LEDs with powder-based phosphors reveal a strong dependence of field lifetimes on environmental conditions such as elevated operation temperature, humidity, corrosive gas and air pollutant exposure. The reason behind this is the design of current white LEDs. They consist of blue light emitting chips and yellow phosphor, which is excited by the blue light and in total produces white light. The yellow phosphor powder is dispersed in a polymer or silicone matrix with low thermal conductivity either placed in a layer directly on, or in a lens above the chip [1]. The packaging of a standard white converter LED is shown in Figure 1.

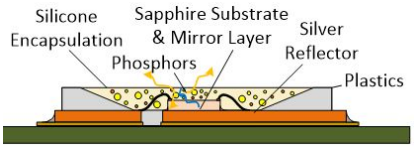

Figure 1: Schematics of a traditional white MID-power LED in plastic package with phosphor powder in silicone matrix.

Continuous improvements of the LED chips enable increasing current and luminance densities, which lead to an extreme photo-thermal strain on the phosphor powder and the surrounding polymer matrix even without external influences. This is particularly enhanced since the stoke-losses in the phosphor when converting blue to yellow light are unavoidable and the chip surface on which the phosphors settles is already the hottest area in the LED device.

Gas permeability of LED packaging materials

Gas permeability and inertness are important factors for encapsulation and packaging materials. The He gas permeability of different materials over time and versus material thickness is shown in Figure 2 for materials commonly used in opto- and microelectronic packaging. The pollutant has to diffuse through the encapsulation first, before being able to reach the silver reflector, p-contact or converter. Thus, the encapsulation should be as impenetrable to gases as possible. Phenyl- and methyl-based silicones are widely used as encapsulation materials for LEDs. Phenyl-based silicones offer a ten times lower gas permeability and at the same time a higher optical index than methyl-based silicones, which facilitates light extraction of the generated light. Methyl-based silicones are general purpose encapsulation materials and are used because of their lower price compared to Phenyl-based Silicones. Epoxy is also used as an encapsulation material. It shows lower gas permeability and a high thermal stability but its low optical index is unfortunate for an LED encapsulation material, since this reduces the light extraction efficiency [3]. On the other hand, glasses, ceramics and metals have an up to 10 orders in magnitude lower gas permeability which facilitate true hermetic operation.

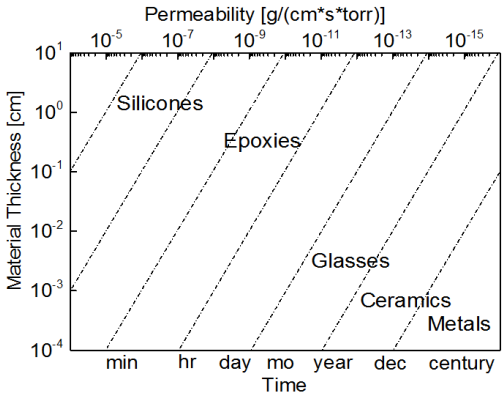

Figure 2: Helium permeability of different packaging materials over time and thickness [8].

Effects of trace gases and air pollutants on LEDs

The presence and concentration of air pollutants depend on the application. Especially lighting applications in the heavy and chemical industry, harsh environments, automotive, agriculture and pools can be affected. But also applications where one would not suspect an accelerated degradation might be concerned, since critical chemical substances are ubiquitous. They are even found to accumulate in the luminaire assembly itself, especially if sealed, since cables and electric components can leak out gases during operation. Penetrating pollutants can accelerate browning and corrosion inside the LED package [4] [5]. This can reduce the lifetime,

cause light losses inside the package and cause color shifts, which the eye can easily recognize when comparing different LEDs. The silver-based reflectors inside the package and the LED chip itself are particularly sensitive in this respect. As an example the effects of the corrosive pollutant H_2S on a mid-power LED with silicone encapsulation are discussed below [6] [7]. In the upper part of Figure 3 a mid-power LED operated in air at room temperature for 380 h is shown. When the device is operated under the same conditions in air with 10 ppm H_2S trace gas a severe darkening of the metal reflector and the bond wires is observed, furthermore the silicone matrix above the chip is clouded. For this particular LED a 70% light loss is measured.

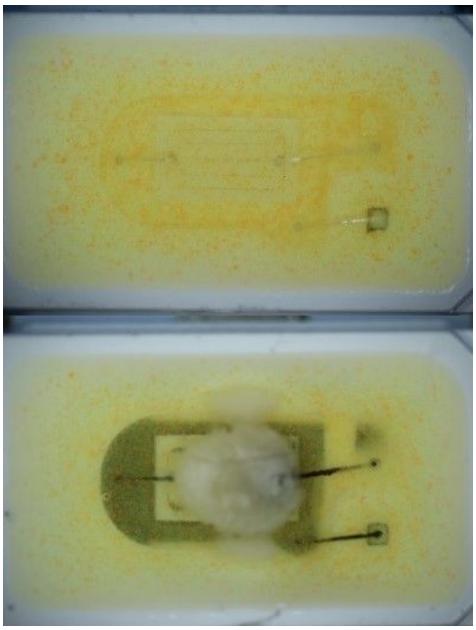

Figure 3: Degradation of a mid-power LED due to operation in pure air (top) and in air with 10 ppm H_2S trace gas (bottom). The diffusion of the corrosive trace gas causes a darkening of the metal reflector and a clouding of the silicone matrix above the chip [6]

Ceramic phosphor development

To solve the problem of thermal degradation, an entirely inorganic converter with a high thermal conductivity is in the focus of research and development. One approach to prepare such a converter is to sinter a polycrystalline ceramic based on YAG phosphor powder [9] [10]. Polycrystalline YAG ceramics for optical application were described first by Ikesue et al.[11] in the middle of the 1990s by mixing Al_2O_3 and Y_2O_3 powders using vacuum sintering. These first ceramics were clearly transparent with about 80% transmittance for visible light without any dopant. In the following years, the YAG was doped with neodymium and the resulting ceramics were used as laser material with properties comparable to YAG:Nd single crystals [12]. Nowadays, instead of phosphor-in-silicone composites, polycrystalline YAG:Ce ceramics, with different levels of transparency, mounted on top of a blue-emitting LED are described for high-power white LEDs [13]. Compared to the phosphor-in-silicone composites the ceramic phosphors have a lower concentration of the expensive cerium dopant, and in addition exhibit excellent optical and thermal stability. The optical properties and the content of scattering centers can be engineered by varying the degree of porosity, the grain structure, and the minority phases [14]. But the main advantage compared to silicone-based converters is the high thermal conductivity of the ceramic ($> 5\,W/mK$) that allows an efficient dissipation of the heat caused by the Stokes losses within the phosphor, thus diminishing the thermal effects on the optical performance. Most recently, the optical properties of transparent, polycrystalline YAG:Ce ceramics were discussed in the literature and Raukas et al. [14] described that the intrinsic scattering by pores induces backscattering, thus leading to absorption within the converter or the LED chip, which should be reduced to achieve a maximum optical conversion efficiency (CE). On the other hand, scattering is required for a homogeneous mixing of transmitted blue and converted yellow light and can be achieved by extrinsic scattering at a rough or structured surface. In combination with a blue (460 nm) LED and under the requirement that 35 percent blue is transmitted to create white light with 5000 K color temperature, the calculated theoretical maximum optical-optical down conversion efficiency is 283 lm/Wopt [13]. The result published in the literature for the luminous efficacy of a 0.63 mm thick YAG:Ce ceramic disk with 0.1 mol% Ce doping was 73.5 lm/W for the complete LED [15]. The transmittance of this ceramic was about 70 percent in the visible range with a 10% transmittance in the blue absorption band at a wavelength of 460 nm and a grain size of about 10 µm with residual pores on the grain boundaries. The data published so far in the literature report on whether the thickness of the specimen or the concentration is a crucial factor, but the data are mostly not clearly comparable and seem to depend on the individual properties, such as increased optical path length due to pore scattering, of the specimen. To study the

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influence of dopant concentration and sample thickness, our ceramics have been applied as converters in conjunction with a blue LED and the effects of concentration as well as the thickness of the polycrystalline disks on the optical properties of the resulting PC LEDs have been investigated [16].

Figure 4: Photograph of translucent YAG:Ce ceramics with 0.5 mm thickness and different content of Ce doping; (a) laying and (b) standing on the background [16].

The yttrium-aluminum garnet ($Y_3Al_5O_{12}$, YAG) polycrystalline disks were prepared by reaction sintering of yttria (99.99%), alumina (99.999%), and cerium oxide (99.995%) in a ratio of Y:Al of 3:5 and with an addition of a different concentration of cerium oxide of 0.1, 0.5, or 1 mol% percent as well as a sintering aid (tetraethyl orthosilicate) under vacuum at a temperature of 1800 °C for 5 h in a furnace with molybdenum lining. The powder mixtures were pressed uniaxially at about 50 MPa and cold isostatically at about 700 MPa to form cylindrical disks. The resulting polycrystalline bulk disks were grinded and polished to the required thickness of around 0.4 mm, depending on the amount of scattering. The microstructure of the completely densified ceramics was dominated by the main phase of $Y_3Al_5O_{12}$ with less than 10 µm grain size. The scattering effect of the translucent ceramic is the result of a secondary phase of alumina located at the grain boundaries. Further details on the preparation, the microstructure and the optical properties are described elsewhere [16].

In order to facilitate wafer-level packaging using large-sized ceramic phosphor wafers the sintering, condensation and wafering process has been scaled up to demonstrate ceramic phosphor wafers with a diameter of 100 mm. An important

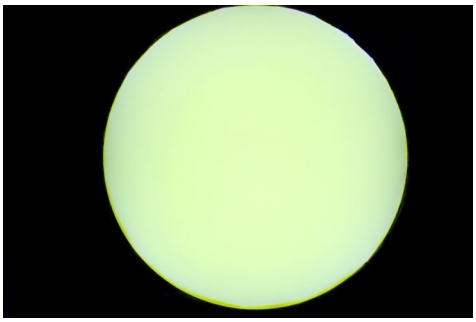

Figure 5: Color and brightness distribution of a 100 mm YAG:Ce ceramic phosphor wafer in a test setup with 460 nm back-illumination.

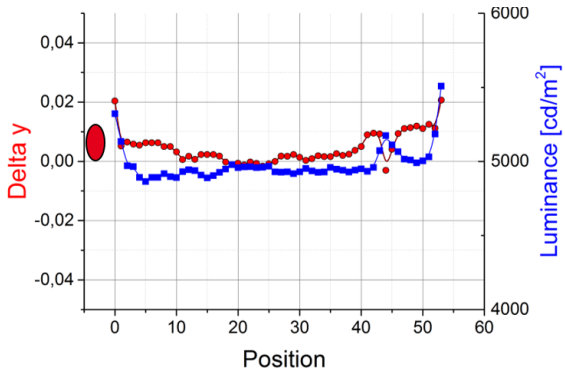

Figure 6: Lateral color coordinate drift ΔCCY (red) and luminance distribution (blue) across a 100 mm ceramic phosphor wafer. Compared to a three-step MacAdams ellipse only a small min-max color drift of $\Delta CCY < 0.01$ is observed.

measure for production yield and LED color binning is the optical homogeneity of the phosphor wafer. To measure the lateral color and brightness distribution the ceramic phosphor wafer was exposed to a homogenous 460 nm LED back-illumination. The resulting color and brightness distribution is shown in Figure 5. The CIE 1931 color coordinates *x* and *y* as well as the luminance has been measured across the wafer using a compact spectral radiometer, see Figure 6. Compared to a three-step MacAdams ellipse only a small min-max color drift of $\Delta CCY < 0.01$ is observed. Also the luminance distribution is very stable across a 100 mm ceramic phosphor wafer.

Different methods such as volume scattering and laser surface μ-structuring have been applied to remove wave-guiding and the angular color distribution in the far-field pattern. An example of a Laser surface μ-structure prepared by ultra-short-pulse UV ablation in a YAG:Ce phosphor wafer is shown in Figure 7. The structure provides extraction facets to avoid light guiding of the yellow light generated inside the

phosphor and to improve the angular far-field pattern. Furthermore, specific dielectric filter and anti-reflection layers have been utilized to improve the conversion efficiency of the phosphor and to reduce light losses and unwanted reflections.

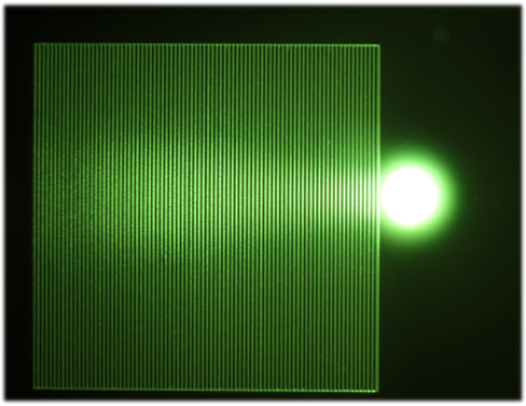

Figure 7: Laser surface μ-structure in a YAG:Ce phosphor wafer. The structure provides extraction facets to avoid light guiding of the yellow light generated inside the phosphor and to improve the angular far-field pattern.

Polymer-free full ceramic LED farbrication

Ceramic phosphors are already used in LED production [13] as chip-level converters which are polymer-bonded on the LED chip and silicone encapsulated. In this work the intension is to demonstrate power-LEDs where the ceramic phosphor wafer is part of the package and is thermally isolated from the LED chip, providing no further thermal burden. Instead the good thermal conductivity of the ceramic phosphor is used to cool of the heat generated by stokes-losses via the package directly into the heat sink. Furthermore, the hermitic nature of the ceramic phosphor is used to form a hermetic polymer-free LED package. To avoid polymer in the package and to achieve hermeticity all parts of the package are eutectic bonded.

The fabrication of the LEDs is based on a wafer-level process with a highly thermal conductive Aluminum nitride interposer wafer, a highly reflective Aluminum oxide spacer and the ceramic phosphor wafer on top. A total of four 3 W power flip-chips are bonded inside the cavity. The outer dimensions of the SMT devices are $4.2 \times 4 \times 1.5\,\mathrm{mm}^3$, see Figure 8.

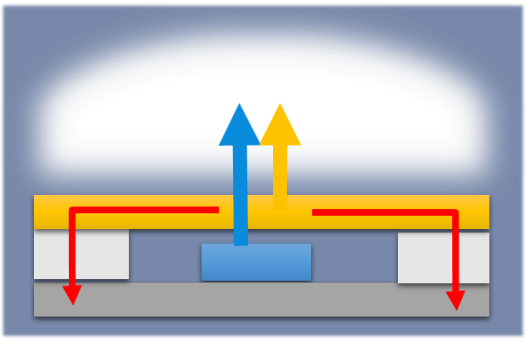

Figure 8: Schematics of the hermetic full-ceramic LED. The phosphor is recessed from the LED chips and forms a part of the package.

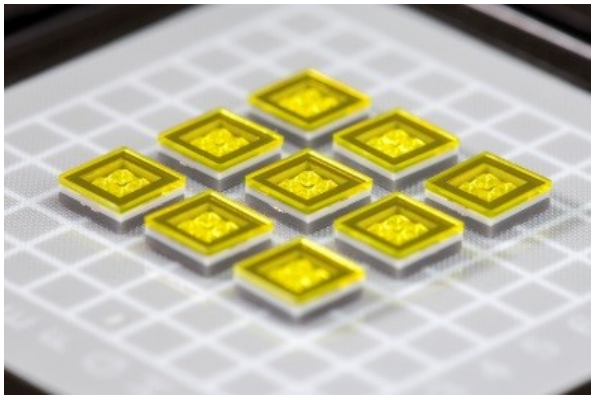

Figure 9: Hermetic high-power 4×3 W full ceramic white LED in SMT package with $4.2 \times 4 \times 1.5\,\mathrm{mm}^3$ device dimensions.

LED device characterization

Extensive optical characterization has been performed on the LED devices to improve the conversion efficiency of the phosphors, to improve the blue emission of the pump flip-chips and to reduce absorption and reflection losses within the package. The luminous efficacy of the polymer-free LED for different drive currents are shown in Figure 9. A maximum efficiency of more than 140 lm/W is achieved a low current with 125 lm/W at a drive current of 350 mA. Although this efficiency is commonly achieved with polymer-packaged LEDs it is a very high value when compared to conventional hermetic LEDs in TO-can package.

Conclusions

Lighting applications in demanding, hot, harsh, polluted or corrosive environments reduce the useful lifetime of conventional LEDs in polymer-package. This is due to the low thermal stability of polymers and their permeability to

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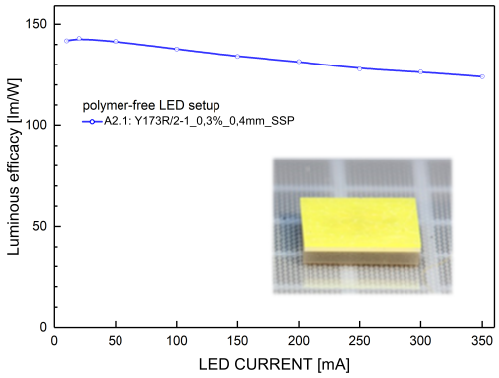

Figure 10: Luminous efficacy vs. LED drive current of a polymer-free full-ceramic LED.

gases. For such applications hermetic polymer-free LEDs have been demonstrated in this work. The LEDs are based on ceramic phosphor which is part of the package. The rest of the package is also full ceramic with eutectic bonding of the individual parts. A SMT device with 4×3 W electrical power and a footprint of $4.2 \times 4.2\,\mathrm{mm}^2$ has been demonstrated. A high luminous efficacy of 125–140 lm/W has been achieved.

Acknowledgment

We sincerely thank our colleague Thorsten Passow for scientific discussions and Mrs. S. Liu for electrical-optical LED characterization. This work was financially supported by the Ministry of Science, Research and Art Baden-Wuerttemberg (MWK) through the Sustainability Center Freiburg within the Pilot project “SusLight”. The ceramic LED phosphor and package development was funded by Fraunhofer within the WISA Projekt HeraKLED.

References

[1] P. Schlotter, R. Schmidt, and J. Schneider: Luminescence or blue light emitting diodes. Appl. Phys. A 64, 417 (1997).

[2] K. Gordon, “Lifetime of White LEDs”, Building Technologies Program, U.S. Departement of Energy, Aug. 2006

[3] Yole Développement SA, “Thermal Management for LEDs and Power Electronics 2017”, pp. 30, p. 172, 2017

[4] P. Singh, C.M. Tan, “Degradation Physics of High Power LEDs in Outdoor Environment and the Role of Phosphor in the degradation process“, Scientific Reports, Nature, Issue Date: Apr. 2016, DOI:10.1038/srep24052

[5] Osram OS., “Chemical Compatibility of LEDs”, Application Note, Feb. 2015, pp. 14–19 [Online] Available: `http://www.osramos.com`

[6] Andreas Zibold, R. Schmidt, M. Zechmeister, H. Konstanzer, M. Dammann and M. Kunzer, Accelerated LED-Degradation under Exposure to Air Pollutants, LED Lighting Technologies LpS 2017, S. 510, September 2017, ISBN 978-3-9503209-8-5

[7] Andreas Zibold, R. Schmidt, M. Zechmeister, H. Konstanzer, M. Dammann and M. Kunzer, Accelerated LED-Degradation under Exposure to Air Pollutants, LED Lighting Technologies LpS 2017, S. 510, September 2017, ISBN 978-3-9503209-8-5

[8] R Tummala and E Rymaszewski, “Microelectronics Packaging Handbook”, Van Nostrand Reinhold, 1989

[9] S. Nishiura, S. Tanabe, K. Fujioka, Y. Fujimoto, and M. Nakatsuka: Preparation and optical properties of transparent Ce:YAG ceramics for high power white LED. IOP Conf. Ser.: Mater. Sci. Eng. 1, 012031 (2009).

[10] H. Bechtel, P.J. Schmidt, A. Tücks, M. Heidemann, D. Chamberlin, R. Mueller-Mach, G.O. Mueller, and O. Shchekin: Fully phosphor-converted LEDs with Lumiramic phosphor technology. In Proceedings of SPIE, Tenth International Conference on Solid State Lighting, Vol. 7784, 2010; p. 77840W.

[11] A. Ikesue, I. Furusato, and K. Kamata: Fabrication of polycrystalline, transparent YAG ceramics by a solid-state reaction method. J. Am. Ceram. Soc. 78(11), 225 (1995).

[12] A. Ikesue and Y.L. Aung: Synthesis and performance of advanced ceramic lasers. J. Am. Ceram. Soc. 89(6), 1936 (2006).

[13] M.R. Krames, O.B. Shchekin, R. Mueller-Mach, G.O. Mueller, L. Zhou, G. Harbers, and M.G. Craford: Status and future of highpower light-emitting diodes for solid-state lighting. J. Disp. Technol. 3(2), 160 (2007).

[14] M. Raukas, J. Kelso, Y. Zheng, K. Bergenek, D. Eisert, A. Linkov, and F. Jermann: Ceramic phosphors for light conversion in LEDs. ECS J. Solid State Sci. Technol. 2(2), R3168 (2013).

[15] S. Nishiura, S. Tanabe, K. Fujioka, and Y. Fujimoto: Properties of transparent Ce:YAG ceramic phosphors for white LED. Opt. Mater. 33, 688 (2011).

[16] K. Wätzig, M. Kunzer, I. Kinski: Influence of sample thickness and concentration of Ce dopant on the optical properties of YAG:Ce ceramic phosphors for white LEDs, Journal of Materials Research 29 (2014), 19, S.2318–2324

Heat Fluxes and Temperatures in Chip-on-Board LEDs for Different Package Structures and Phosphor Technologies

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Abstract

Several failure mechanisms appear in LED packages at diverse locations. Since the processes are thermally accelerated, the precise determination of temperature leads to better lifetime calculations. The use of structure functions from thermal transient measurements helps to analyse the thermal behaviour of several package elements. The package's encapsulation has an impact on the dissipated thermal power. Ceramic phosphor layers show higher thermal conduction in comparison to silicone layers. Despite large geometrical differences surface temperatures of the encapsulation behave similar for high power and multi-chip-on-board LED packages.

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Introduction

The knowledge of temperature at different locations in LED packages is important for several reasons. Failure mechanisms appear at diverse locations, so the exact temperature helps to calculate the package's lifetime. Moreover, the emitted radiation is reduced at high temperatures with different ratios considering the chip or phosphor.

Packages for chip-on-board LEDs vary in the geometry in comparison to high power LEDs. Especially the surface area of the silicone encapsulation is larger than the die's dimensions in many products. This leads to new considerations of the heat flux, in order to estimate the package's thermal management.

After discussing the heat transfer of LED packages in general, the thermal influence of different elements like the phosphor layer and encapsulation are analysed. In the last part silicone temperatures are described as a function of the driving current.

Heat transfer in LED packages

Sorts of heat transfer

In general, three kinds of heat transfer exist: conduction, convection and radiation [1].

The one dimensional heat conduction through a plate with surface A, thickness d and thermal conductivity λ can be calculated by

$$P_c = \lambda \cdot \frac{A}{d} \cdot (T_2 - T_1). \quad (1)$$

In case of thermal convection, the particles of a fluid like air or water transport the energy. The coefficient α is difficult to calculate and therefore often determined empirically.

$$P_k = \alpha \cdot A \cdot (T_2 - T_1) \quad (2)$$

The radiation behaves different to conduction and convection, the temperatures have the exponent four in the equation. Every material has its own emission coefficient ε, that represents the ability of radiation.

$$P_r = \sigma \cdot \varepsilon \cdot A \cdot (T_2^4 - T_1^4) \quad (3)$$

These three equations are used to estimate the heat dissipation of LED packages.

High power and chip-on-board LED packages

A standard high power LED package includes a chip with phosphor layer, that is encapsulated by a dome of silicone. For this package the heat dissipation should be examined by approximate calculations. The encapsulant is a hemisphere with a diameter of 2 mm. For a silicone temperature of 120 °C and an ambient temperature of 25 °C a thermal power of only 10 mW is dissipating by radiation and convection using formula (2) and (3). In comparison with a thermal energy of 1000 mW, it would be only 1 %, so negligible. That is why the main heat must be transported by conduction.

In a multi-chip-on-board package, the dimensions of the encapsulant and chip differ. The larger surface of the silicone leads to a higher thermal dissipation of about 1000 mW regarding convection and radiation and the temperatures applied before. Since the multi-COB package can be driven with high electric energies, the thermal power can be up to 100 W. The amount of the heat transfer by convection and radiation still lies at only 1 %.

As the heat conduction plays the main role, some of heat conductivities are shown in the following table:

Table 1: Thermal Conductivities.

Material	Thermal conductivity in W m^{-1} K^{-1}
Air	0.026
Silicone	0.2–0.5
Ceramic	10–50
Copper	300

Experimental Study

In order to study the different heat fluxes inside a package, three package structures are analysed: a bare chip, a chip with a phosphor layer and an encaspulated chip with layer. Always the very same LED packages have been varied during the tests. A transient thermal testing system (T3ster) provides the main measurement results. The chip's temperature is determined by its voltage, that can be sampled with an interval of few

microseconds. The radiant power is measured by a spectrometer that is connected to an integrating sphere. The thermal power of the LED package is then calculated by the difference of electric and radiant power.

As shown in the section before, the main part of the heat flux is transported by conduction into the board. Since the silicone material is directly attached to the chip, the heat will also flow through the encapsulation to the board (Figure 1).

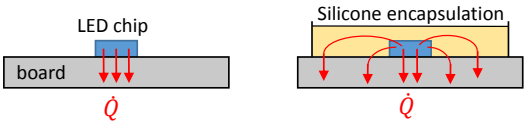

Figure 1: Heat flux in chip-on-board LED packages: a bare chip (left) and a chip with silicone encapsulation (right).

Heat fluxes

Heat fluxes are quite difficult to measure inside an LED package. That is why first the chip's temperature has been studied for the different structures. If there is a change of the heat flux, the temperature should also vary.

Temperature increase

After inserting electric energy into the LED system, the chip is heated and its temperature rises. The heat is flowing from the bare chip downwards into the board. After placing a phosphor layer onto the chip, the heat system is changed. An additional heat source appears inside the phosphor layer, because the blue radiation is converted into yellow radiation with lower energy. An encapsulation will also have an influence on the package's thermal behaviour. The following diagram shows the temperature rise after supplying 700 mA to the LED package.

Because of the additional heat source, the temperature rise of the chip plus layer is higher than for the bare chip. But after encapsulation, the temperature rise gets lower again. This is a hint, that the silicone might have a cooling effect on the system.

Since the thermal power is different for every condition (Table 2), new temperatures are calculated for a thermal power of 1 W. These new curves are presented in the next figure.

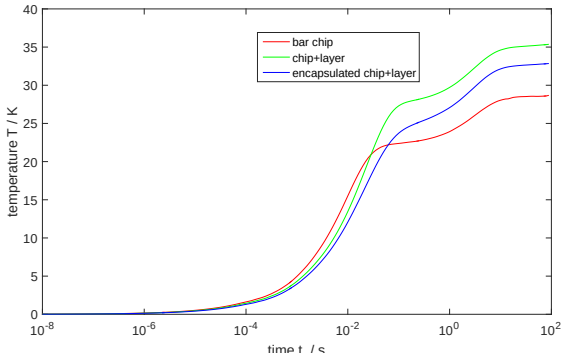

Figure 2: Temperature increase of an LED chip, driven by 700 mA with different package components: bare chip, chip with layer, layered chip inside encapsulation.

Table 2: Thermal power for a constant current of 0.7 A.

Package structure	Thermal power
bare chip	1.09 W
chip+layer	1.37 W
encapsulated chip+layer	1.49 W

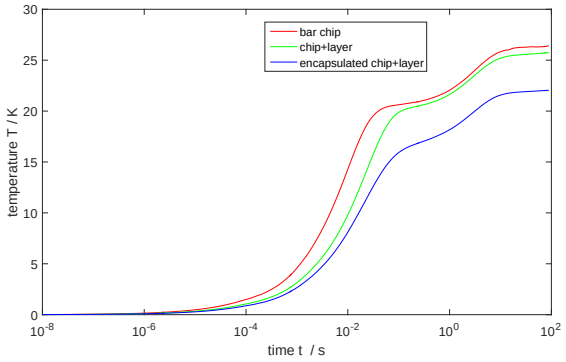

Figure 3: Temperature increase of an LED chip, for a thermal power of 1.0 W, with different package components: bare chip, chip with layer, layered chip inside encapsulation

Now the curves for the bare chip and chip with layer are close to each other. That is because the curves are normed to the same heat power of 1 W. The temperature rise of the layered chip is even a bit less. The curve of the encapulated chip is lying clearly under, so it is obvious that the encapsulation is reducing the temperature inside the chip, in regard to the same heat power.

Structure Functions

The evaluation of the thermal measurement is based on a network of many RC elements in a chain. Every element is represented by a dot in

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the so called structure function. This cumulative function gives a thermal view into the package. The thermal resistance is placed on the abscissa, the thermal capacity on the ordinate in logarithmic scale. Steep sections accord to regions with a high thermal conductivity and capacity like metals. Horizontal parts belong to materials with a low thermal conductivity and capacity like dielectrics.

Parallel resistance

For a package including a silicone phosphor layer two thermal transient measurements are shown in Figure 4. The red curve shows the structure function before the encapsulation. The increasing part to the right of 22 K W^{-1} represents the board. The main part of the long horizontal path can be related to the dielectric layer [2].

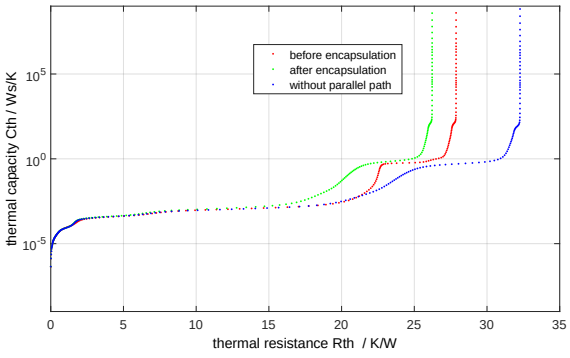

Figure 4: Thermal structure functions for a chip-on-board LED with ceramic phosphor layer.

After encapsulation the right part of the structure function is shifted to the left (green curve). Up to 10 K W^{-1} the two curves are congruent, so the thermal resistance until the electric layer has not changed significantly. The part of the dielectric region is smaller, because one part of the heat flux flows through the silicone down to the board (Figure 1). That is why the surface area of the dielectric layer is now larger, where the heat flux is coupling into. This circumstance leads directly to a smaller thermal resistance (equation (1)).

The described parallel path has an influence on the structure function, but is not quantified yet. For the evaluation it is possible to attach a resistance in a parallel way to the whole chain. The new structure function shows the thermal behaviour of the system without the parallel path in order to get closer to the main heat flux.

In this paper the parallel thermal resistance is determined in the following way: the blue curve represented to the system including a parallel path should be congruent to the red curve of the package before encapsulation. Parallel resistances for a phosphor layers with silicone and ceramic matrix are presented in the following table.

Table 3: Thermal resistances using silicone and ceramic layers.

Total LED package	Silicone layer	Ceramic layer
Simulated thermal resistance	32 K W^{-1}	35 K W^{-1}
Parallel thermal resistance	140 K W^{-1}	60 K W^{-1}
Resulting thermal resistance	26 K W^{-1}	22 K W^{-1}

The parallel thermal resistance of the silicone layer is more than twice as high as the resistance of the ceramic layer. The better thermal conductivity of ceramic leads to a stronger heat flux from the chip through the layer into the silicone encapsulation. The total thermal resistance of the simulated system and the parallel path are calculated like two parallel electric resistances:

$$R_{\mathrm{th,total}} = \frac{R_{\mathrm{th,c}} \cdot R_{\mathrm{th,p}}}{R_{\mathrm{th,c}} + R_{\mathrm{th,p}}} \qquad (4)$$

The values for the LED package with a silicone layer can also be identified in the last vertical part of the structure functions.

Temperatures in multi-COB LEDs

A multi-chip LED consists of many chips that are arranged in parallel chains. The silicone encapsulation fills the spaces between the chips and contains the phosphor material. With high forward voltages like 40 V and currents of 4 amperes the electric energy is about 160 W in this case. With a efficiency of 40 % nearly 100 W is generated as thermal power. Only the very small thermal resistance of these COB moduls realises such high powers. The determination of the temperature can be done at measurement points on the surface of the module. They have a direct contact to the board.

The board's temperature is not equal to the chips's temperature. The chip is directly bounded to the metal board, so that the difference is only small. The conversion inside the phosphor material leads to a heat source inside the silicone encapsulation. Since the thermal conductivity of

silicone is smaller than the board, higher temperatures should be appear at the surface.

Silicone is a good emitter of infrared radiation, its emission coefficient is about 0.95. So thermal cameras can measure the surface temperature. The temperature inside the encapsulation is important to know, because some degradation processes are taking place there.

For one multi-COB package the surface temperatures for different forward currents at a controlled board temperature of 55 °C have been measured. The temperature is increasing in a linear way with higher currents. At 500 mA the surface temperature is about 60 °C, at 2000 mA about 80 °C. The package uses a volume emitter, because all phosphor particles are equally distributed inside the encapsulation.

Same investigations on high power LED packages with a phosphor layer are also resulting in a nearly linear function of the encapsulation's temperature and the driving current. So there is no a difference between volume emitters and phosphor layers for this relationship.

Conclusions

This paper studies the heat fluxes and temperatures in LED packages. Thermal transient measurements are adequate to get results for samples where information of exact material composition and structure is not available. Especially the silicone encapsulation influences the heat flux inside the package. The introduced method with the quantification of parallel resistance can help to classify different phosphor and encapsulation technologies regarding their thermal behaviour.

The comparison of silicone and ceramic phosphor layers show a higher reduction of temperature for the ceramic matrix. Further research should study the temperature distribution inside the encapsulation and the board temperature measurement points. First results show that the use of metal or ceramic as a board material have to be considered if conclusion from the external measurement point to the internal temperatures are done.

Acknowledgment

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References

[1] H. D. Baer, K. Stephan, Wärme- und Stoffübertragung, Springer, 2006.

[2] H. Zhang, M. Wagner, T.Q. Khanh, Comparing New Dielectric Materials for Chip-on-Board LED Packages, LED professional Review, January 2017.

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Advancements in LED Technology Enabling High-Luminance LEDs

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Abstract

Recently, high luminance has become a key requirement for LEDs used in directional lighting applications such as stage, sports, and retail lighting. Increased LED luminance (flux per LED luminescent area per unit solid angle) enables luminaires with narrower beam angles, smaller secondary optics, and improved light usage fostering energy efficiency. Driving LED luminance to 100 Mnits and beyond requires specialized product architectures and advancements in LED technology involving epitaxy, LED chip, phosphor, and package. In this paper, we review relevant developments in these technologies enabling high luminance LEDs with performance meeting stringent application requirements for directional lighting.

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Introduction

Since their commercial introduction in 1993, [1] Light Emitting Diodes (LEDs) based on the III-Nitride materials systems and phosphor conversion have conquered the lighting industry as the light source of choice. Continued improvements in efficacy, reduced form factor, proliferation into a broad range of whites (correlated color temperature, CCT, and color rendering index, CRI), robustness and reliability, and, most importantly, reductions in price have allowed illumination-grade LEDs to push out conventional light sources from essentially all new lamp and luminaire designs. Today, depending on device architecture, CCT/CRI, and drive current density, LEDs deliver efficacy of 150 to 200 lm/W as a source. Figure 1 illustrates the efficacy evolution of III-Nitride based white LEDs since 2004.

For these LEDs it is important to characterize the efficacy depending on current density due to the "droop" phenomenon. "Droop" refers to the reduction of the LED efficacy with increasing drive current [2] which is typically observed for this materials system as implemented in commercially relevant LEDs.

We further differentiate LEDs based on their architecture. Mid- and low power LEDs use a plastic package and a lateral LED chip with a phosphor-silicone mix filled into the package. High power LEDs typically use a ceramic interposer and a silicone dome. The LED chip used in high power packages is usually more complex and uses either a thin-film flipchip (TFFC) or vertical thin-film (VTF) architecture. More recently, chip-scale-package flipchip (CSP-FC) architectures have been employed [3]. Due to the lower cost of mid power LEDs, they are typically driven at lower drive current density and, hence, provide high efficacy. On the other hand, high power LEDs provide high flux from a smaller optical source size due to their construction and their typical operation at higher current densities.

Besides efficacy, luminance is an important performance characteristic of LEDs. It fundamentally describes the ability of the primary emitter to provide photons from a source area into a solid angle. The more photons are emitted from a smaller optical source and directed into a smaller solid angle the higher the luminance. An extreme case is a laser diode which can have luminance about 1 order of magnitude higher than

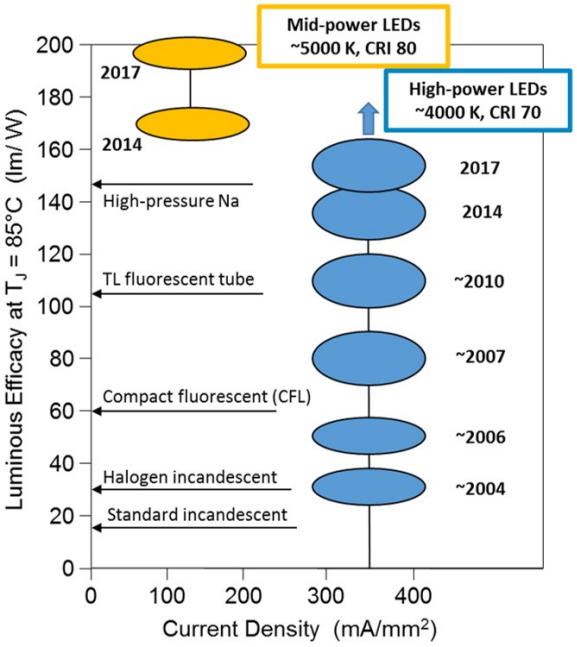

Figure 1: Luminous efficacy vs current density for high power and mid power emitters based on III-Nitride pump LED chips. The ellipses depict approximate operating conditions and performance at the year indicated. The blue color refers to high power while the amber color is for mid power LEDs. Mid power LEDs have been used for lighting applications for about the last 5 years. For comparison, approximate source efficacies of conventional lighting technologies are also indicated.

an LED. High luminance is especially critical for applications where the beam exiting the lamp or luminaire is shaped by an optic (lens or reflector) and the size of the optic or narrowness of the beam is of importance. This requirement is best characterized by étendue" [4] which needs to be minimized at the emitter level to enable small form factor optics, narrow beams, and uniform beam mixing.

Étendue, G, is constant throughout an optical system and represented as function of the emitting source area, S, and the solid angle of the emission distribution, Ω:

$$G = \iint dS * d\Omega \qquad (1)$$

Thus, for narrowest beam systems, étendue must already be minimized at the light engine or LED level. A high luminance LED will enable optical systems with minimized étendue by providing emission from a small source size with a well-controlled beam pattern.

The benefit of high luminance LEDs in directional

applications is illustrated by an optical system model where two LEDs are placed under the same secondary optic and the resulting beam profile is analyzed as shown in Figure 2. Luminous intensity normalized to flux (cd/lm) is shown as a function of angle. The standard LED is a state-of-the-art, domed high power emitter with a 4 mm^2 die. The dome facilitates light extraction but effectively magnifies the source to an optical source size of close to 11 mm^2. The high luminance LED is an un-domed high power emitter with the same die size and otherwise same technology elements. The impact on beam properties can be modeled by tracing ray models for both LEDs through the same secondary optic to a far-field receiver. The narrower the profile the more light is channeled into a narrow beam by the secondary optic.

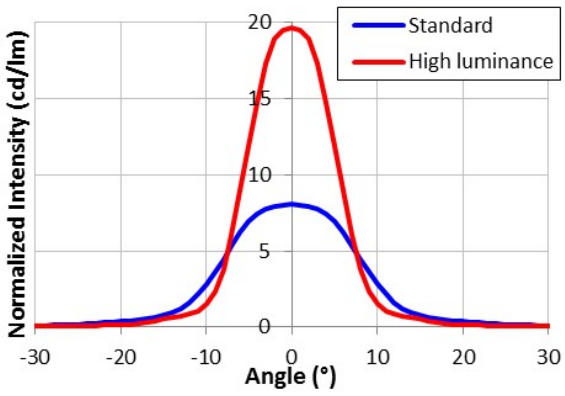

Figure 2: Modeled intensity profiles of a spotlight with a domed standard LED and an un-domed high luminance LED using the same TIR optic.

The results, as illustrated in Figure 2, show that within a FWHM beam angle of 11.4°, 77% of the flux of the high luminance LED is contained vs. 58% of the flux of the standard LED. While the removal of the dome reduces the efficacy of the high luminance LED by about 10% at the same drive conditions, in this case from 493 to 442 lm, the better optical control enabled by the high luminance LED results in a net gain of delivered light of about 19%.

In the following sections, we will further describe the LED performance metric “luminance”, review LED technology advancements related to high luminance LEDs, discuss high luminance LED package options, and give the example of a specific LED designed for high luminance before concluding in the final section.

Luminance

Light sources are often described by “brightness”. In fact, “brightness” is a non-quantitative parameter describing perception of a light source [5]. Almost always perceived brightness is related to the physical parameter called luminance.

Luminance (L_v) is defined as luminous intensity of a light source in a given direction per unit area of the source. Usually, luminance is in the direction perpendicular to the surface of the light source and given by:

$$L_v = \frac{I_v}{S} = \frac{d^2\Phi_v}{dS * d\Omega} \qquad (2)$$

where I_v is luminous intensity and S the emitting source area. Φ_v is the luminous flux and Ω is the solid angle of emission distribution. The unit of luminance is candela per $meter^2$ cd/m^2 or nit. A typical computer display has a luminance between 50 and 300 nit. The filament of an incandescent bulb has a luminance of 1×10^6 nit. The sun has luminance of about 1.6×10^9 nit.

There are several methods of measuring luminance [6]. For well-defined sources, the average luminance can be derived by dividing luminous intensity by source area. Luminous intensity can be measured by standard gonio-photometers. The advantage of this method is ease of calibration and the ability to measure a range of light sources with different spectrum. Disadvantages are inability to measure luminance for sources without sharp borders and the fact that only average luminance for all emitted light is measured. These disadvantages can be overcome by using spectrometer based luminance meters. In these instruments a lens and aperture define the area from which light is accepted by the spectrometer. An illustration of the concept behind such an instrument is shown in Figure 3.

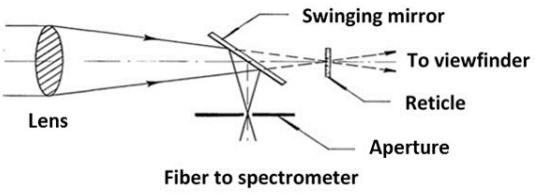

Figure 3: Schematic of a spectrometer based luminance meter. Key functional elements are depicted [6].

Finally, for pixel-by-pixel luminance measurements, scientific grade, three-filter

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cameras can be used. Disadvantage of this method is that it requires complex calibration procedures by one of the two methods described above.

LEDs differ significantly in luminance from hundreds of kilonit in low-power to hundreds of meganit in high intensity, automotive headlight LEDs. Various LED packages are shown in Figure 4 and sorted by luminance and flux. Four LED categories can be distinguished. Mid power LEDs have low luminance and light output. “Arrays” or Chip-on Board (CoB) LEDs deliver higher luminance and span a wider range of flux output levels. Domed high power and super-high power (die sizes > 2 mm) emitters form the next category. Un-domed high power emitters and LEDs designed for automotive forward lighting deliver highest luminance reaching 100Mnit and above.

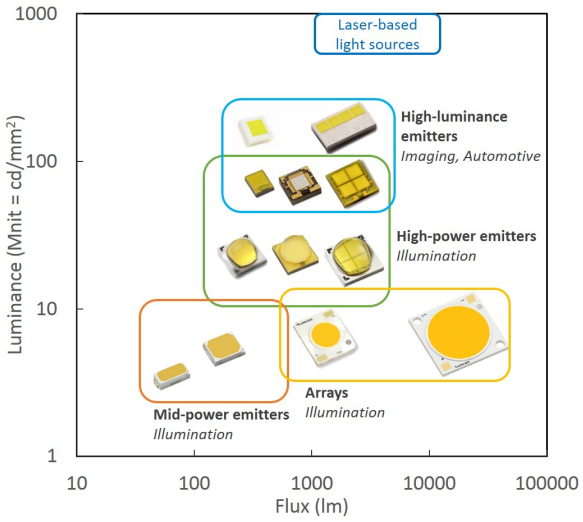

Figure 4: Luminance vs flux for relevant LED types. The ranges of performance in luminance and flux are indicated by colored boxes.

LED Technology

Increasing the luminance of III-Nitride based LEDs can be achieved by increasing the drive current capability of the LED, as well as by confining the source size from which light is emitted. Both approaches exhibit a penalty in LED efficacy: increasing the drive current reduces efficacy due to epitaxy droop, current crowding in the die [7], and photo-thermal saturation in the phosphor [8], whereas a smaller source size typically reduces efficacy through lower package efficiency [9]. In fact, optimization of the efficacy of an LED often reduces its luminance.

The luminous efficacy of an LED (η_L), which is essentially a measure of efficiency, evaluated in terms of the response of the human eye is commonly represented by the product of four factors: the internal quantum efficiency of carrier recombination in the active region (*IQE*), the extraction efficiency of photons in the blue LED (*EXE*), the electrical efficiency of the injection of carriers into the active region (*ELE*), and the efficiency of converting blue photons into the desired LED spectrum. The conversion efficacy (*CE*) is generally sub-divided into: the package efficiency (*PE*), the luminous equivalent of the emission spectrum (*LE*), the quantum efficiency of down conversion by phosphors (*QED*), and the quantum deficit (*QD*), which represents the Stokes shift penalty. Hence, η_L is given by:

$$\eta_L = IQE * EXE * ELE * CE \tag{3}$$

and,

$$CE = PE * LE * QED * QD \tag{4}$$

Figure 5 illustrates values of the individual efficacy components according to equations (3) and (4). Typical values for all these efficiencies are given for two classes of LEDs: A typical InGaN-based high power LED designed for Illumination, e.g., streetlighting (in 4000 K, CRI 70 and 3000 K, CRI 80), which has been optimized for efficacy and an LED used in Automotive front lighting, which was optimized for luminance.

As expected and depicted in Figure 5, penalties exist for the luminance-optimized LED primarily in internal quantum, electrical, and package efficiencies. Furthermore, a high luminance LED used in illumination applications may include additional efficiency penalties associated with warm-white CCT and high CRI (e.g., 2700 K CRI 90), adding luminous equivalent and quantum efficiency of down conversion to the list.

In this section, we will further highlight technology challenges existing specifically for high luminance LEDs. Opportunities will be discussed for advancements in epitaxy (*IQE*), die design (*EXE* and *ELE*), and converters (*QED*). Optimization of LED packages (*PE*) will the topic of section 4.

Epitaxy

It is now well accepted that the ubiquitous efficiency “droop” present in InGaN based LEDs is due to Auger recombination in InGaN quantum

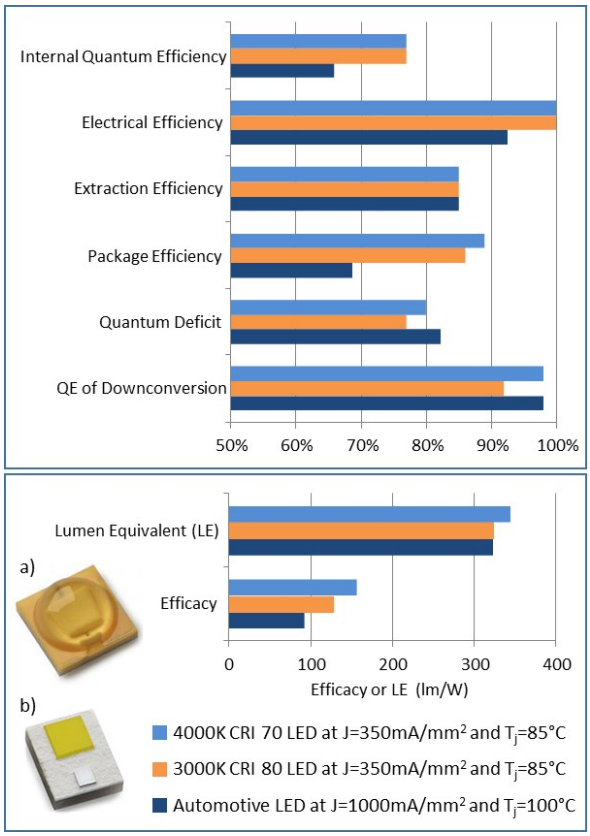

Figure 5: Breakdown of efficacy components for typical cool-white and warm-white phosphor-converted high power illumination LEDs at $J = 350\,mA/mm^2$ and $T_j = 85\,°C$, as well as for a typical high power automotive front-lighting LED at $J = 1000\,mA/mm^2$ and $T_j = 100\,°C$; a typical high power general-illumination LED and a typical high power automotive front lighting LED are depicted and labeled a) and b), respectively.

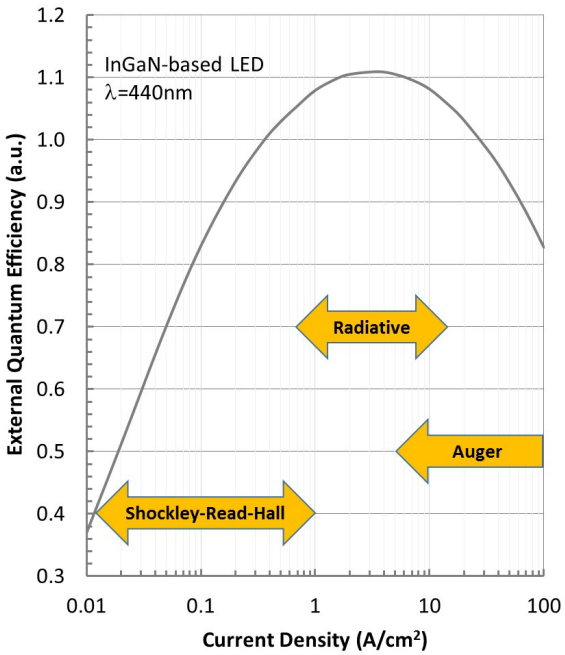

Figure 6: External Quantum Efficiency (*EQE*) of an InGaN based LED with a peak emission at 440 nm vs forward current density. Three distinct operating ranges are present as indicated by the arrows: "Shockley-Read-Hall", SRH loss dominates; "Radiative", radiative recombination dominates; "Auger", Auger recombination begins dominating and extends to current densities beyond shown in the graph.

wells [10]. Auger recombination robs carriers by recombining an electron and a hole to elevate a third carrier into a higher energy state without emitting a photon. The Auger recombination coefficient for InGaN has been established to allow for this process to be relevant at carrier densities commonly present in InGaN quantum wells at drive currents typical for high power LEDs.

Figure 6 displays a typical efficiency curve of an InGaN based LED emitting at 440 nm.

Three distinct operating ranges can be discerned which are marked by arrows in the figure. Shockley-Read-Hall (SRH) recombination dominates at low drive current density followed by a range where radiative recombination reaches its maximum. At high operating current density, Auger recombination starts dominating the output characteristics of the LED. Obviously, highest luminance is achieved in this operating range.

While the Auger recombination coefficient is fundamental to the InGaN material employed and in fact increases with increasing InN composition [11], strategies have been devised to reduce its impact. Key is to lower the carrier density in the quantum wells as the Auger recombination has a cube dependence on carrier density [2]. However, growing InGaN quantum wells thicker quickly runs out of steam as the materials quality deteriorates with increasing thickness. This results in point and structural defects which increase SRH recombination [12], [13]. Using active regions with multiple quantum wells and lower composition barriers is a better strategy but limited by carrier spreading due to the asymmetry in electron and hole effective masses of the III-Nitride materials system [14]. Here, band structure engineering is the key to create active regions with high IQE even in the "droop" regime. This can promote better carrier distribution and ensure a lower carrier density per quantum well.

A band structure diagram for an example multiple quantum well active region is illustrated in Figure 7. Different scenarios of carrier spreading and material quality are simulated by adjusting the

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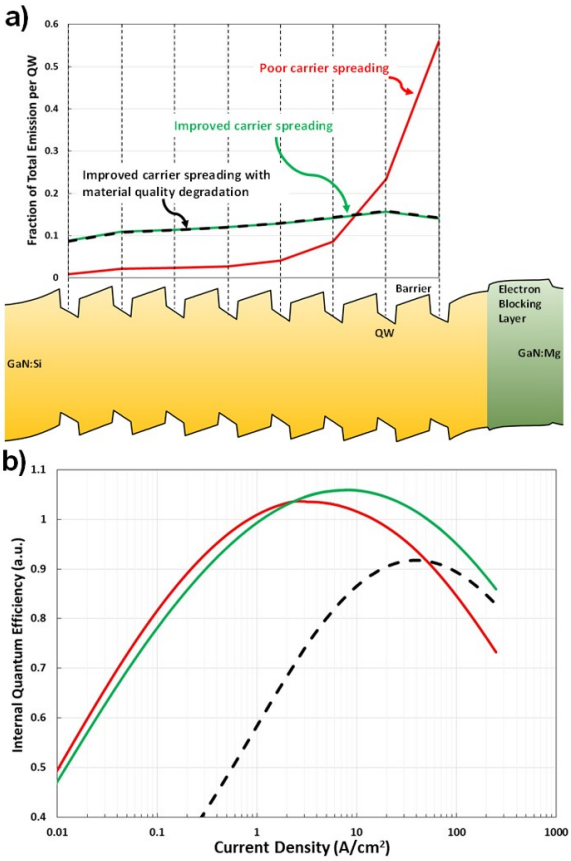

Figure 7: One-dimensional device simulations of LED active regions with different carrier distributions and material quality (a). Shown is the contributing fraction of each quantum well to the total emission as function of position in the multiple quantum well stack which is indicated as a band structure diagram of the active region. The orientation of the active region in the LED layer structure is indicated by the position of the n-layer (GaN:Si, left) and the p-layer (GaN:Mg, right). The corresponding dependence of internal quantum efficiency (IQE) on drive current density as modeled is shown in (b).

input hetero-structure design and non-radiative recombination lifetimes, respectively. Carrier spreading across the multiple quantum wells is shown for three different scenarios in Figure 7a, while the resulting efficiency vs drive current density is shown in Figure 7b. Moving from a poor carrier spreading structure (red lines) to an improved carrier spreading structure, but with poorer material quality (black dashed lines), provides gain at only very high current densities. In comparison, an improved carrier spreading structure with no material quality degradation (green lines) offers significant high current gains over the poor carrier spreading baseline.

"Droop" is further promoted by the presence of internal electrical fields due to piezo-electric polarization at the well-barrier interfaces in the active region of the LED. The piezo-electric polarization at hetero interfaces is a consequence of the preferred growth direction in the polar c-direction of this materials system on c-plane sapphire substrates [16]. This arrangement is prevalent for all commercially viable LEDs as devices with alternative configurations based on semi or non-polar growth generally result in LED performance that is inferior [17], [18] and LEDs that are more costly than LEDs with straightforward c-plane growth. Again, proper engineering of the active region can mitigate the impact of electron-hole separation and improve the efficacy of high luminance LEDs.

Chip Design

The objective of the LED chip (or die) in an emitter designed for high luminance is to achieve highest light extraction from the smallest emitting area while providing the overall flux output required for the application. The flux required per emitter may determine the die size but the die construction together with the package design will dictate the achievable luminance.

Candidate chip structures are identified in Figure 8 where (a) thin-film flipchip (TFFC), (b) chip-scale package flipchip (CSP-FC), and (c) vertical thin-film (VTF) (c) die designs are illustrated. The TFFC die is an ideal choice as it combines high extraction efficiency with pure top surface emission [19]. However, it requires mechanical support via a ceramic submount that adds manufacturing complexity and cost. CSP-FCs avoid these complexities and have advanced to the point where they compete with thin-film die in extraction efficiency [3]. However, the presence of the sapphire substrate with a thickness of typically about 100 µm leads to substantial side emission (5-sided emitter) which would render this architecture unsuitable for high luminance applications. Hence, CSP-FCs need to be "side-coated" with a high-quality reflective coating as is shown in Figure 8b. Then, CSP-FC combines pure top-emission with high robustness, high drive capability, and is directly mountable on a PC-board to enable close-packed arrays. VTF die also combine pure surface emission with high extraction efficiency, however, the required wire bond and the presence of a host-substrate limit their ability to be used in densely packed arrays.

The optimization of the extraction efficiency as

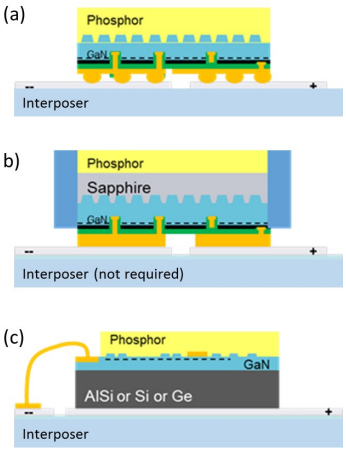

Figure 8: Die architectures suitable for highluminance emitters. Shown are schematic illustrations of (a) Thin-film flipchip (TFFC), (b) Chip-scale package flipchip (CSP-FC) with side-coat, and (c) Vertical thin-film (VTF) die. Note that the drawings are not to scale: the epitaxial growth is typically 5.0–10 µm, the sapphire layer about 100 µm, and the phosphor layer 50–100 µm thick.

part of chip development focuses on achieving the extraction of blue photons from the die on first pass without reflecting photons back into the die where they may be absorbed. The absence of a high refractive index silicon dome for thin-film architectures or the presence of the optical side coat hamper this objective and multiple bounces can be expected [20]. As a consequence, reducing the opportunity of photons to be absorbed in the die becomes paramount.

The greatest contributor to this absorption is the GaN-Ag interface. Traditionally, Ag formed the electrical contact to the p-layer of the LED chip but also served as mirror to form an optical cavity tuned to optimize light extraction in a thin-film die architecture [19]. One way to address this weakness is to switch to a composite contact structure, formed by interposing a sufficiently thick, low-index oxide layer between the metal and the semiconductor.

Figure 9 illustrates the layer sequence of a pure Ag contact (Figure 9a) and the composite contact using ITO, SiO_2, and Ag (Figure 9b). Also shown is the improvement in reflectivity vs wavelength (WL) and angle of incidence (AOI) switching from a pure Ag mirror to the composite structure. Selecting SiO_2 prevents light incident within a critical cone angle of approximately 40° from interacting with the metalization. The reflector loss contribution can then fall from about 50% to just about 20% percent, according to our simulations.

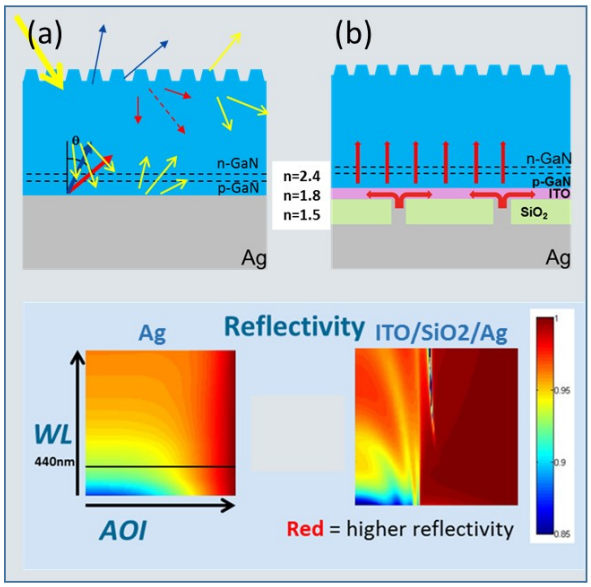

Figure 9: Comparison of (a) *Ag*-only and (b) *ITO*/SiO_2/*Ag* composite p-contact structure. For each case, relative reflectivity (red is high, blue is low) as wavelength (WL) vs angle of incidence (AOI) graph is included. Potential scattering events are depicted with colored arrows in the schematic for the *Ag*-only contact, and for the composite structure the refractive indices of the layers are shown.

Another benefit arising from the introduction of the composite contact structure for high luminance LEDs is superior current spreading. Current crowding associated with areas of high current density leads to “local droop” and reduces the efficacy of LEDs driven at high currents.

Converter

Mirroring the reduction in internal quantum efficiency of the InGaN active regions, the quantum efficiency of the luminescence in phosphors decreases non-linearly with excitation density.

Figure 10a shows relative conversion efficiency of a warm-white, thin-film LED versus the blue light irradiance arriving from the pump LED for three different temperatures and normalized to a typical LED operating point of 85 °C and 35 A cm^{-1}. The conversion efficiency decreases with increasing temperature and light ouput of the pump source. Comparing to the droop of the underlying pump LED, the phosphor droop contributes 25% of the total decrease in efficiency of the integral warm-white LED [8].

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Figure 10b shows measurements of quantum efficiency of down conversion of phosphors representative of those used in high power LEDs for Illumination: cerium-doped aluminum garnet and Eu-doped red nitride phosphor (here represented by $(Ba, Sr)_2 Si_5 N_8$:Eu. The quantum efficiency measurement is performed with the phosphor sample temperature controlled externally and under a pulsed optical excitation to avoid additional heating. The efficiency reduction in Eu^{2+} red nitrides shows strong dependence on temperature; therefore, the phenomenon of phosphor droop is often referred to as photothermal quenching (PTQ). The Cerium-doped aluminum garnets show little dependence of photo-quenching on temperature. Further investigations into the nature of the quenching process in $(Ba, Sr)_2 Si_5 N_8$:Eu showed that the decrease in efficiency is closely predicted by quadratic dependence on the concentration of excited europium activators [8].

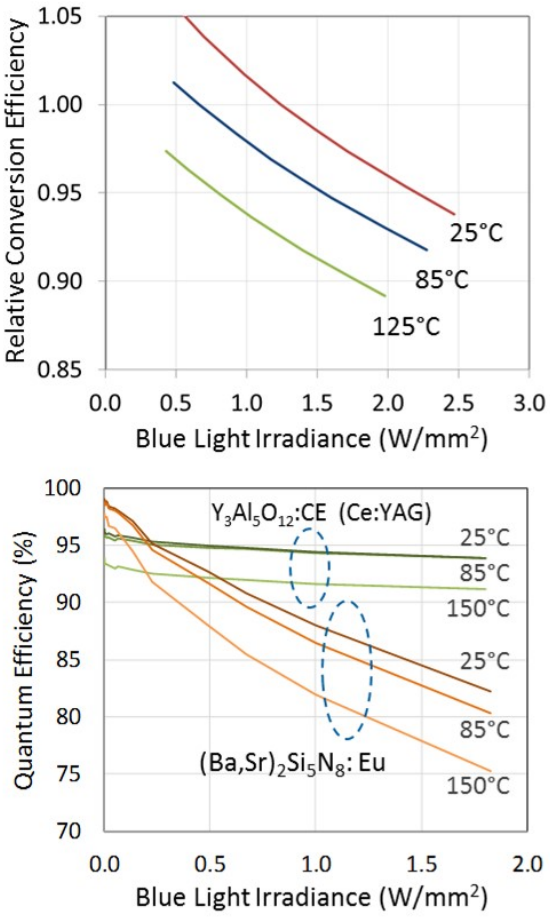

Figure 10: (a) Conversion efficiency quenching in a warm-white high power LED versus blue light irradiance and for phosphor temperature. (b) Examples of photo-thermal quenching in common phosphors used in high power LEDs.

The dependence of quenching on the excited activator concentration points to two possible ways to reduce the droop: lowering activator doping level and increasing the volume of the converter. The drawback of such approaches is that the emitting area of the optical source increases and, hence, does not address high luminance applications. Ultimately, for the highest luminance applications, PTQ needs to be controlled at phosphor-material level and further study of the root cause and materials design parameters are required.

Product Architectures

LEDs utilizing a TFFC or VTF die are generally good choices for high luminance LEDs as they enable high efficacy via enhanced blue light extraction, facilitate easy converter integration, and create uniform surface emission. The phosphor layer is typically applied as thin converter film over the die mounted on a ceramic substrate. After singulation the LED is encapsulated with silicone molding. The silicone layer provides protection as shown in Figure 11a. Despite this packaging benefit, flat lens molding with practical molding thickness widens the angular radiation distribution which is a drawback for applications requiring high luminance.

LED luminance can significantly be enhanced by employing the structure with compact converter layer on a TFFC die and reflective side coating as shown in Figure 11b. Free of the flat lens, the TFFC based emitter architecture provides all the advantages described earlier with a Lambertian, forward directed emission pattern.

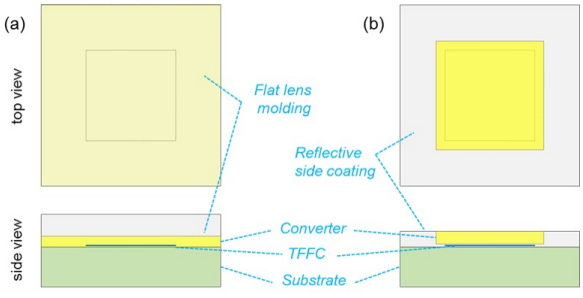

Figure 11: Schematic diagram of high luminance LED structures with (a) flat lens molding over the converter layer and TFFC, and (b) side reflector molding around the converter and TFFC on ceramic submount.

The integration of a CSP-FC die into an LED package provides another path for creation of a high luminance emitter. The sapphire template, used for initial epi growth, remains and serves as

optical media. CSP-FC based LEDs eliminate the need for a foreign substrate reducing cost. CSP-FC LEDs with conformal converter layer and flat molding can enable high efficacy while maintaining a compact dimension as shown in Figure 12a. The distributed light in the sapphire reduces photo thermal quenching. However, the 5-sided emission associated with this architecture significantly widens the angular radiation distribution, reducing the luminance of the source. Side emission is often lost by the luminaire optics, and may cause optical cross talk and loss when CSP LEDs are assembled in a closely-packed array.

In order to maintain high luminance, light emission must be limited to the top surface only. As shown in Figure 12b, a side reflective coating with a clear silicone fillet redirects light to the phosphor layer covering the entire top surface. This converts the volume emitter into a surface emitter while maintaining high package efficiency; however, the source size is increased substantially and the structure is prone to have poor color-over-angle (strong yellow light at high angles). This problem can be resolved by introducing a full side reflector coating to the CSP LED chip as well as the converter layer as shown in Figure 12c. This structure has lower package efficiency as more light is reflected back into the LED die (necessitating a highly reflective die as discussed above) but allows optical source size to approach the lateral dimension of the CSP-FC die.

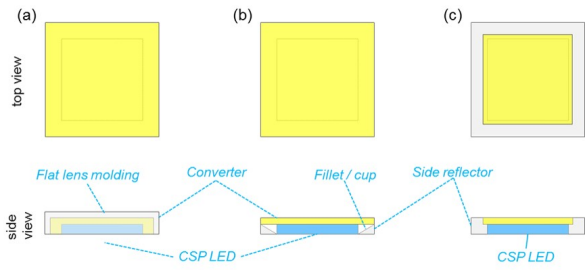

Figure 12: Schematic diagram of high luminance CSP-FC LED structures. (a) 5-sided emitter, (b) fillet-enhanced surface emitter, and (c) surface emitter with full side reflector coating.

Furthermore, the array packing density can be further increased with this architecture, minimizing the size of an optical system as shown in Figure 13.

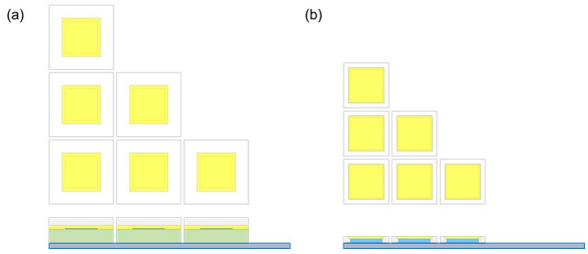

Figure 13: Schematic diagram of high luminance emitter arrays based on (a) TFFC and (b) CSP-FC.

Example of a high luminance LED

A dedicated, high luminance LED is LUXEON CZ which was market released by Lumileds in March 2018 [21]. This LED employs a no-dome, thin conformal overcoat architecture, the benefits of which are described further below. Images of this LED which is available in a broad range of colors and white CCT/CRI configurations are shown in Figure 14.

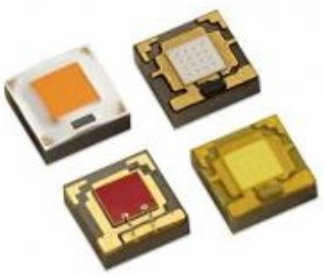

Figure 14: LUXEON CZ high luminance LEDs. Amber (top-left), blue (top-right), white (bottom-right), and red (bottom-left) emitting LEDs are shown.

Applications for high luminance LEDs are primarily architectural, signal, and entertainment (stage) lighting. In these applications total luminaire size is of great importance.

In architectural illumination, it is important to achieve maximum effect while being able to hide the luminaire in limited spaces. Smaller LED and optics size will allow for smaller housing and efficient and low cost water protection. Signaling lights are mostly vehicle mounted and aerodynamics limits the size of the luminaires there. In some cases it is desired to make these luminaires the least obvious when not in service. In entertainment lighting, small size is important as the luminaire will potentially block the view of the spectator.

A properly designed emitter addresses markets

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requiring high luminance, high center beam candlepower, and those systems needing minimal cross talk between emitters in close packed applications all in a small form factor. étendue is minimized at the emitter level. Specifically, this is achieved by not including a dome or a flat lens which would enlarge source size and broaden radiation pattern. Suitable is a LED with a thin-film chip and with a thin, conformal silicone protection (thickness $<<$ die dimension).

The apparent source area that a system and secondary optics will see is not only based on the LED chip or die size, but also, what type of scattering material may be applied to it and the shape and refractive index of the encapsulating material. It is well characterized that a chip encapsulated by a hemisphere of silicone (traditional dome) will produce an apparent source area of $\approx 2\times$ the chip area. Although doming an emitter may give gains in efficacy, the source area and étendue has been increased by $2\times$.

Mechanical and environmental protections which traditionally were provided by the dome shaped encapsulation are still needed even in a non-domed, thin film-based LED. A flat encapsulation by a molding process is easy to manufacture and cost-effective way to protect the LED. It does present, however, the need to increase the thickness of the flat molding to an undesired total height due to manufacturing variations. The needed typical thickness allows a significant amount of light to be emitted from the sides of the encapsulant, where rays appear to originate from a different location than rays emitted from the top of the encapsulant. This enlarges the apparent source size and thus contributes to an increased étendue. A thin conformal and non scattering overcoat provides mechanical and environmental protection while having a minimal interaction with the light emitted from the LED source. The optical source size is decreased and the radiation profile contains only light emitted through the top surface, in other words, it preserves the smallest possible étendue.

A straightforward way to analyze this benefit is to use a source imaging goniometer to measure the rayset of the LED. This rayset contains all relevant étendue information. The performance of different LEDs in a directional application can then be compared by ray tracing the raysets of each LED with reference luminaire optics. Figure 15 shows such a comparison with measured raysets of a domed, flat-lens, and thin conformal encapsulated LED, evaluated through a generic reflector optic.

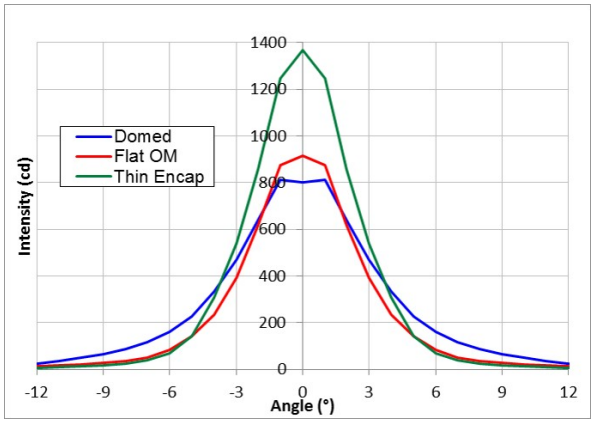

Figure 15: Intensity vs beam angle generated with a narrow beam reflector lens. Three different LEDs are used as indicated: A domed high power LED ("Domed"), a flat-lens LED ("Flat OM"), and LUXEON CZ ("Thin Encap") featuring thin encapsulation.

A figure of merit for the performance of the LED/lens combination is the maximum achievable "punch" or on-axis intensity value per given LED lumen. Relevant performance parameters are summarized in Table 1. The thin conformal encapsulated high luminance LED achieves $2\times$ "punch" vs flat lensed and domed emitter ($\approx$ 76 vs $\approx$ 50 and $\approx$ 33 cd/lm, respectively). It also achieves favorable beam parameters, beam angle (BA, FWHM at 50% peak intensity) and field angle (FA, beam width at 10% peak intensity). Further, the optical efficiency of the overall system is improved, and the on-axis intensity characterized as center beam candle power (CBCP) is highest for the thin-encapsulated LED.

Table 1: Beam parameters for the situation depicted in Figure 15. Beam angle (BA), field angle (FA), optical efficiency, punch and center beam candle power (CBCP).

Encapsulation	Domed	Flat Lens	Thin
BA (°)	7.0	5.4	5.0
FA (°)	16.6	11.7	10.1
Optical Eff. (%)	92	87	95
Punch (cd/lm)	33.0	49.7	76.4
CBCP (cd)	793	894	1375

Conclusions

Technology development in III-Nitride epitaxy, chip design, phosphor down converters, and LED packages has advanced to offer illumination grade LEDs not only exceeding conventional lighting technologies in efficacy but also allowing for design flexibility previously not possible. Emitters can be optimized for high luminance to enable spot lights with narrow beam shapes achieving high light utilization efficiency or slim light fixture designs without the need for large reflectors or lenses. This capability is fostering the adoption rate of LEDs in illumination applications, as lamp and luminaire designers chose LEDs for their unique capabilities and consumers select LED-based fixtures for their differentiated design.

LED technology development is poised to continue advancing the capabilities of LEDs and enable emitter designs that further increase luminance:

- Epitaxy development with focus on improving the IQE not only at typical operating conditions but also at high drive currents alleviating droop
- Chip design with emphasis on reducing absorption of photons in the die and the optimization of current spreading to avoid imbalance in local current densities improving EXE and ELE
- Converter development opportunities exist in identifying phosphor materials that have narrow emission spectra, high quantum efficiency, and minimized photo-thermal quenching to boost LE and QED at high drive operating conditions
- Finally, package technology plays a key role optimizing the integration of die and converter to maximize PE and allow close packing of LEDs with minimized package sizes while maintaining desired radiation profiles.

LEDs have been shaping the trajectory of lighting enabling new and differentiated light fixture and luminaire designs. This trend will continue and eventually non-obtrusive light fixtures based on optimized high luminance LEDs will be the norm in general illumination. Lighting will seamlessly integrate into buildings, building controls, and the Internet.

Acknowledgment

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References

[1] S. Nakamura, T. Mukai, and M. Senoh, Appl. Phys. Lett. **64**, 1994, 1687–1689.

[2] Y. C. Shen, G. O. Mueller, S. Watanabe, N. F. Gardner, A. Munkholm, and M. R. Krames, Appl. Phys. Lett. **91**, 2007, 141101.

[3] Jy Bhardwaj, John M. Cesaratto, Isaac H. Wildeson, Henry Choy, Ashish Tandon, Wouter A. Soer, Peter J. Schmidt, Benno Spinger, Parijat Deb, Oleg B, Shchekin, and Werner Götz, Phys. Status Solidi A, 1600826, 2017

[4] Julio Chaves, Introduction to Nonimaging Optics, 2nd. ed. Boca Raton: CRC Press, 2016, ch. 4

[5] Federal Standard 1037C, the Federal Glossary of Telecommunication Terms, 1996

[6] Casimer DeCusatis (editor), Handbook of Applied Photometry, ed 1, Optical Society of America, New York: Springer Verlag, 1998, ch. 5

[7] Ashish Tandon, Toni Lopez, Oleg Shchekin, Isaac Wildeson, Parijat Deb, Henry Choy, and Jy Bhardwaj, Compound Semiconductor, Vol. 23, Issue 2, 2017, 36

[8] O. Shchekin, Compound Semiconductor **22**(6), 2016, 26.

[9] Michael R. Krames, Oleg B. Shchekin, Regina Mueller-Mach, Gerd O. Mueller, Ling Zhou, Gerard Harbers, and M. George Craford, Journal of Display Technology, Vol. 3, No. 2, 2007, 160

[10] J. Iveland, L. Martinelli, J. Peretti, and J. S. Speck, C. Weisbuch, Phys. Rev. Lett. **110**, 2013, 177406.

[11] J.-R. Chen, Y.-C. Wu, S.-C. Ling, T.S. Ko, T.C. Lu, H.-C. Kuo, Y.-K. Kuo, S.C. Wang, Appl Phys B **98**, 2010, 779–789

[12] M. Leyer, J. Stellmach, Ch. Meissner, M. Pristovsek, M. Kneissl, Journal of Crystal Growth **310**, 2008, 4913–4915

[13] N.G. Young, R.M. Farrell, S. Oh, M. Cantore, F. Wu, S. Nakamura, S.P. DenBaars, C. Weisbuch, and J.S. Speck, Appl Phys Lett **108**, 2016, 061105

[14] Masakatsu Suzuki, Takeshi Uenoyama, and Akira Yanasem Phys. Rev. B **52**, 1995, 8132

[15] Fabio Bernardini, Vincenzo Fiorentini, Appl Surface Science **166**, 2000, 23–29

[16] F. Scholz, Semicond. Sci. Technol. **27**, 2012, 024002

[17] Hisashi Masui, Shuji Nakamura, Steven P. DenBaars, and Umesh K. Mishra, IEEE Transactions on Electron Devices, Vol. 57, No. 1, 2010, 88

[18] Jongjin Jang, Seohwi Woo, Daehong Min, and Okhyun Nam, J. Nanosci. Nanotechnol. Vol. 15, 2015, 1–13

[19] Y.C. Shen, J.J. Wierer, M.R. Krames, M.J. Ludowise, M.S. Misra, F. Ahmed, A.Y. Kim, G. O. Mueller, J.C. Bhat, S.A. Stockman, and P.S. Martin, Appl. Phys. Lett.**82**, 2003, 2221

[20] J.J. Wierer, D.A. Steigerwald, M.R. Krames, J.J. O'Shea, M.J. Ludowise, G. Christenson, Y.C. Shen, C. Lowery, P.S. Martin, S. Subramanyam, W. Götz, N. F. Gardner, R. S. Kern, and S.A. Stockman, Appl. Phys. Lett. **78**, 2001, 3379

[21] LUXEON CZ datasheet (2018), `https://www.lumileds.com/uploads/706/DS198-pdf`

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Rapid Evolution of High-Power LEDs Package from SMD to CSP to Direct Mountable Chip

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Abstract

In recent years, Chip-Scale Package (CSP) LEDs have been introduced to certain lighting applications. Compared to conventional Surface-Mount Device (SMD) high-power LEDs, the CSP technology has improved on design compactness and thermal management. Nowadays, the adoption of Direct Mountable Chip has increased to ensure reliability and optimum performance of LED lighting fixtures. In this paper, we first explain how the Direct Mountable Chip technology is providing similar advantages as CSP, over DIP and SMD package. We also discuss several benefits of the new solution to overcome CSP limitations at module level. Then, we give an outlook of the Direct Mountable Chip integration in wider lighting applications by maximizing flux density and introducing color LEDs.

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Introduction

The multiple light sources packages available on the lighting market have contributed in the adoption and quick transitioning to LED markets. The wide range of packages is helping the transition and answers different market needs and demands. One of the focus is to reach higher performances such as the increase of efficacy and luminous flux of the LEDs. Increase in Color Rendering Index (CRI) has also been a recent need and the newest LEDs are developed and designed to meet stronger specifications. Additionally, many Correlated Color Temperatures (CCT) as well as monochromatic LEDs must be made available. Some of the latest LEDs technologies are related to development in the LED chip and the phosphor layer. For Direct Mountable Chip LEDs, Nichia's research and development is focus on packages improvement to deliver higher optical performances and design flexibility.

From DIP to SMD to CSP LEDs

An LED consists on 3 different core technologies: the chip, the phosphor, and the package (Figure 1) [1][2]. The LED chip releases energy in form of photons that will generate the luminous flux. The phosphor layer allows the definition of chromaticity characteristics. As for the package, it protects both the chip and the phosphor.

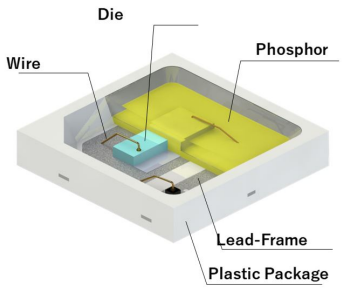

Figure 1: Structure of an LED.

Several decades ago, Dual in-line package (DIP) LEDs were commercialized. The DIP LEDs came first as monochromatic. White DIP LEDs were introduced in the late 90s, for the first time in the world by Nichia. The invention revolutionized the solid-state lighting market. The LED had a low luminous efficacy as DIP LEDs do not have any heatsink components and so have a very poor thermal management. The chip is packaged in an epoxy resin lens where light is emitted in a highly collimated beam angle at around 30°. Despites the high intensity and a good control of the directivity due to a lens, the beam angle limits the light extraction and the designs for different lighting applications. In addition, driving at a low current, thermal management and performance are not optimum, making lighting system miniaturization difficult with DIP LEDs.

Early 2000s, SMD type started to mature. Two technologies of chip are used: traditional or flip-chip. The chromaticity characteristics are identical to DIP LEDs with the addition of multi-color from several chips in a single package. The important development was made on package size with height going down to less than 1 mm. Because of the optimized size, it is possible to obtain higher beam angles. The SMD LEDs reflect less light than DIP LEDs and consequently a better contrast can be achieved. The technology allows also a decrease in step macadam binning and a wider choice of flux step binning. Additionally, the quantity of LEDs on a PCB can be higher to increase the overall system luminous flux. Regarding reliability, lifetime is higher than for DIP LEDs.

Later, performance improvements came with the High-Power LEDs, generally driven at current above 100 mA. The packaging integrates an optic contributing to a better light extraction and increasing the LED luminous flux. At system level, optical designs with secondary optics improve the performances compared to a SMD type system. Despites a better optic compatibility, High-Power LEDs generate more heat. The thermal management within the LED is critical as it impacts reliability. The thermal design, for better heat extraction, is essential to lower the thermal resistance. Finally, cost is higher than for a SMD type LED.

Early in 2010s, Chip-Scale Package LEDs emerged with a major design change on packaging. The LED package is generally to the size equivalent to the LED chip, or no larger than 20% [1]. Consequently, by removing part of the packaging to its minimum and because LEDs are based on flip-chip technology, less raw materials are needed with no holder and wiring, reducing the production processes for a cost reduction. CSP LEDs can be driven at comparable current level as SMD type LEDs. Due to the compact size of the package, they can achieve higher performances in lumen density. Additionally, the thermal management is optimum, reducing the

thermal resistance and improving further the reliability.

Direct Mountable Chip technology provides similar advantages as CSP, over SMD package

Direct Mountable Chip LEDs have emerged in 2015. Focusing on the package optimization, they are comparable to traditional CSP (Figure 2).

Figure 2: Comparison of different LED technologies.

The cost reduction, in term of raw components used and manufacturing processes reduction, brings a competitive solution to the market (Figure 3).

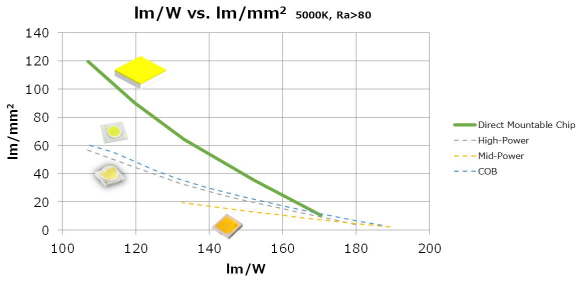

Figure 3: Direct Mountable Chip lm/mm^2 positioning to other SMD and High-Power packages.

Due to the optical small footprint, an advantage over SMD type is that the new LEDs produce higher lumen density [1]. Additionally, under same current compared to SMD, better performances are achieved for luminous flux and efficacy. The heat dissipation is also similar to a traditional CSP, improving thermal management to a SMD type, reducing the thermal resistance and consequently improving the lifetime.

Several benefits of Direct Mountable Chip solution to overcome CSP limitations at module level

Maximizing System Luminous Flux

Direct Mountable Chip LED is composed of a small white silicon resin package that contributes to light extraction (Figure 4). The white walls allow higher internal reflection within the package and consequently more excitation at the phosphor layer. Light emitted from the chip is excited at the phosphor and the absorption is minimum due to the inter-reflections. The light is finally emitted from the entire top surface of the LED to obtain a higher luminous flux output and a higher luminous efficacy.

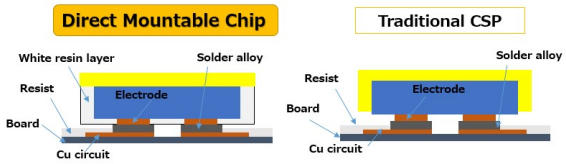

Figure 4: Structures of a Direct Mountable Chip LED and a Traditional CSP.

A typical CSP will emit from the top surface and from its sides. When mounted closely to each other on a PCB, an LED will emit light that will interact with the neighborhoods LEDs (Figure 5). This side emitted light contributes to a higher luminous flux output at LED level but would generate a flux loss at system level as the light can not be extracted easily as the top emitted light can be. Direct Mountable Chip is a top emitted LED only and the output luminous flux can be extracted to its optimal, at system level, with the usage of an optic. Less inter-reflections at PCB level are expected and the system optical loss should be minimized.

Reducing LEDs Mounting Gap

As mentioned, with CSP sources, light interacts with the LEDs placed closely. The Direct Mountable Chip technology avoids most of the interactions and the crosstalk is minimal [3]. Having a minimal crosstalk as light emitting from one LED will less degrade the phosphor of the other LEDs. Consequently, side emitted light has a negative effect as it generates phosphor

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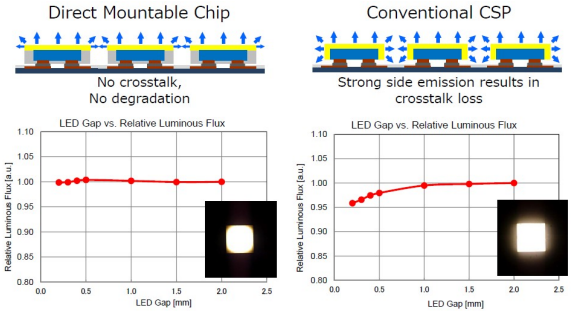

Figure 5: Gap between Mounted LEDs on a PCB versus the Relative Luminous Flux at board level.

degradation at PCB level. Additionally, color shift will occur with traditional CSP (Figure 6). The closer the LEDs are mounted on a PCB together, the more light interactions there are, from one phosphor to another, generating a chromaticity change for each LED. With side walls, the LEDs can be mounted closely to each other with a limited color shift. This helps reducing even more the system design size.

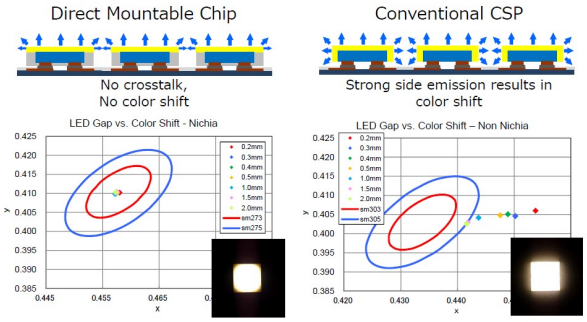

Figure 6: Gap between Mounted LEDs on a PCB versus the Color Shift at board level.

Reducing Risks at Reflow Process

Finally, the mounting on a PCB can generate some reliability issues with a traditional CSP. Because the phosphor layer is very close to the electrical pads, a contact with the solder alloy and the phosphor might occurs more than with a Direct Mountable Chip which is protected by its packaging, the white walls. Excessive presence of solder balls or high amount of solder alloy can generate wicking. Wicking increases degradation of the phosphor, reducing LED lifetime and optical performances (Figure 7).

In traditional CSP, whisker could also occur with small risk for short circuit. Whisker can occur when using lead-free solder alloy which grows as needle shape. Several factors will grow whisker

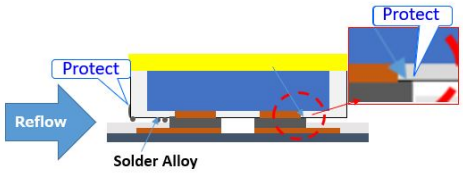

Figure 7: Low Risk of Short Circuit and Light Absorption due to protection from Excessive Solder Alloy.

such as heat cycle, moisture, external stress, electro migration. In a Direct Mountable Chip LED, the chip is protected by its packaging to avoid any short circuits.

Direct Mountable Chip integration in wider lighting applications by maximizing flux density and introducing color LEDs

Direct Mountable Chip LEDs benefits allow the introduction to new lighting applications (Figure 8).

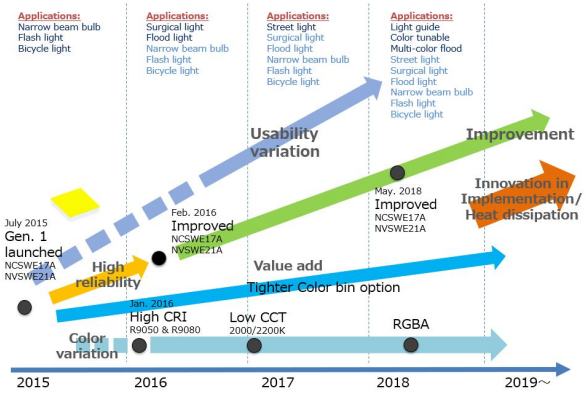

Figure 8: Direct Mountable Chip LED Applications Trends.

Spot Light with Tunable White

The design flexibility is one of the key benefits for spot light with tunable white. Because of no crosstalk, color shift is minimized even for higher density layout with gap less than 0.2 mm. It overcomes the conventional design issue with white LEDs where color point is shifted to yellow as the gap between LEDs becomes narrower. With no color shift, it is possible to make precise color tuning for tunable white. With the small footprint of the LEDs, color mixing can be

achieved with a standard reflector and homogeneous color distribution could be obtained with no additional diffuser, simplifying fixtures' design and reducing cost.

Flood Light Application

Flood lighting application can also integrate Direct Mountable Chip solution as small foot print, maximum flux density and less crosstalk enable super High-Flux module designed with luminous flux over 40k lumens to 100k lumens with small light emitted surface LEDs. The light module should contribute to minimize optics and luminaires' size.

Outdoor LED Luminaires

Street lighting fixtures are also moving to design with Direct Mountable Chip. Because LEDs have small footprints, the intensity distribution can be designed to control road illuminance patterns for better homogeneity and stronger cut-offs with optimum coefficient of utilization of light. Reducing the size of an outdoor luminaire is also possible with optimized light engine, saving on die cast housing and tooling cost. Regarding long term reliability, Direct Mountable Chip do not contain silver and poor resin material, reaching lifetime over 70k hours for L80B10 at Tj = 100 °C.

Designing Thinner Lightguide

Mid-Power LEDs are currently used for base lighting with lightguide optics applications. Because of the 3030 packages' size, lightguide thickness should be more than 3.0 mm to avoid optical loss. With Direct Mountable Chip technology, a better coupling efficiency between LED and thinner lightguide can be achieved. Because of small mounting LEDs gaps in linear modules, color mixing within lightguide is better and the fixtures' color distributions should be more homogeneous.

Color Variation Direct Mountable Chip

Finally, to improve color quality, lower cost and reduce complexity of architectural lighting systems, we have focused our research and development on LED phosphor conversion achieving color expansion for Direct Mountable Chip package [4]. We can expect an acceleration of market adoption for color LEDs to enhance space and to create engaging atmosphere in lighting designs.

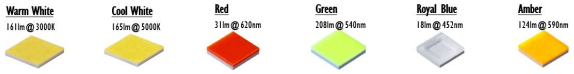

Figure 9: Performance of luminous flux for phosphor converted CSP LEDs with Tc = 25 °C, at If = 350 mA.

Using the same technology platform for the full range, we achieve comparable or higher performance in luminous flux (Figure 9) to other existing market solutions with an additional similar behavior of temperature characteristics between the color line-up [4].

Conclusions

The LED technology is evolving fast. The technology implementation must also be fast and available for a wide range of applications. Direct Mountable Chip technology brings many benefits for not only a successor solution to CSP, but also reaching out to lighting markets where LEDs are replacing traditional light sources. As an LED manufacturer, we must ensure reliability, optimum performances and better quality of light and continue to develop LED light sources based on phosphor conversion to answer current needs for reducing optical and electrical complexity, providing flexibility in design with more compact luminaires.

References

[1] K. Haraguchi, Direct Mountable Chip — Nichia Original White Chip Technology. LED Lighting Technologies — Smart Technologies for Lighting Innovations. Luger Research e.U.. September 2016.

[2] M. Amiya, K. Fujio, T. Suzuki, S. Wakui, Red Component for Horticultural Lighting. Phosphor Global Summit, San Diego, CA, USA. Conference Paper, March 2018

[3] F. Mirand, How innovative LED package technology enables new solid-state lighting designs. European Business Press. eeNews, November 2017, pp. 28–30.

[4] X. Denis, K. Haraguchi, Spectral Optimization with Phosphor for Enhancing Performance of LED device. The 16th International Symposium on the Science and Technology of Lighting. Sheffield, UK. June 2018.

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New Human-Centric Lighting Based on TRI-R Spectrum Technology

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Abstract

Since the development of the fluorescent lamp about 80 years ago, lighting technology using artificial light has advanced. In recent years, the use of light-emitting diodes (LEDs) for lighting has rapidly spread with the aim of energy saving. In addition, the research on the physiological effects of light on human bodies, particularly on the circadian rhythm, has advanced, and the idea that human-centric lighting may contribute to realizing healthier lives has been proposed.

In general, natural light and artificial light are defined in terms of brightness and color temperature. However, the spectrum of current artificial light is markedly different from that of natural light (e.g., sunlight,flame or incandescent lump; black-body radiation). In this article, the new concept of human-centric lighting is introduced, focusing on a spectrum that represents the quality of light.

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Introduction

When we consider the relationship between humans and light from the time humans appeared, we find that biologically, historically, and culturally, light has had a significant meaning to humans rather than simply being a tool to look at objects. For example, in various languages worldwide, in addition to its physical meaning, the word “light” is sometimes used to indicate hope, love, and blessing. In addition, candlelight has been used in many sacred rituals, indicating that humans associate light with a spiritual aspect. Visual stimulation via light, such as by the colors of flowers, colors in nature, and twilight, is associated with aesthetic consciousness. Illumination is also considered as a form of art.

As explained above, the relationship between humans and light has a common denominator that goes beyond ethnicity, age, region, and time. We consider that light is deeply and essentially associated with human physiological functions, particularly those that sustain life, that have evolved in association with sunlight over millions of years.

Considering the consistent association between light and human physiological mechanisms, the technology for sunlight-spectrum-reproducible white LEDs, called TRI-R spectrum technology, was developed, focusing on the optical spectrum with the aim of enhancing human well-being in natural state.

In this article, we will review the history of studies on the relationship between human well-being and light, which has been attracting much attention recently, and then discuss the importance of focusing on the light spectrum from the viewpoints of the structure of human photoreceptors and the principle of vision. Next, the difference between the spectra of sunlight based on black-body radiation (natural light) and recent artificial light is clarified and an outline of TRI-R spectrum technology that can reproduce the sunlight spectrum is presented.

Background of human-centric lighting and the significance of the spectrum

Light has two types of effects on humans. One is direct effects; for example, high-energy light damages the retina, which may lead to age-related macular degeneration. The other is indirect effects as tuning factors for the circadian rhythm. Such effects are closely related to various mechanisms of living bodies, and many studies have been carried out on circadian rhythm disorder. This type of disorder is focused on in this article. Figure 1 shows the reports and information that have been accumulated thus far, which are considered important in relation to the trend of human-centric lighting.

In 2001, it was reported that the secretion of melatonin (a hormone in the body) is inhibited by exposure to light with a wavelength of 446–477 nm.[1] Melatonin is related to the internal clock and controls the rhythm of sleeping and awakening. This is a very important finding, after which researchers started focusing on the relationship between light and the circadian rhythm.

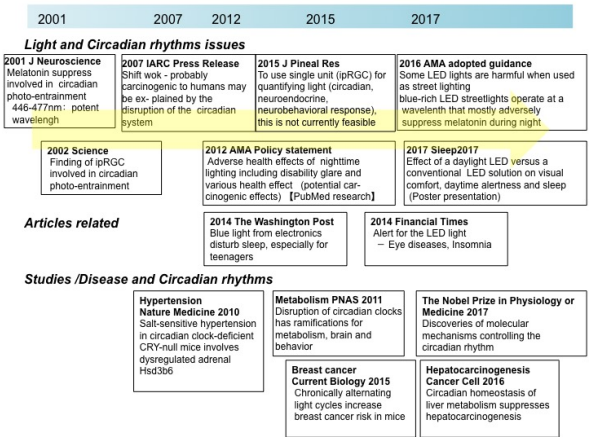

Figure 1

In 2007, the International Agency for Research on Cancer (IARC) pointed out the relationship between shiftwork that may cause circadian rhythm disorder and the development of cancer [2] After that, studies on the causal relationship between circadian rhythm disorder and hypertension[3] and that between circadian rhythm disorder and metabolism[4] were carried out. Thus, the effects of light on human physiological functions started to be examined

from the viewpoint of circadian rhythm disruption or disorder. American Medical Association (AMA), Washington Post, and Financial Times also reported the risks of light exposure during night time[5][6]

The discovery of intrinsically photosensitive retinal ganglion cells (ipRGCs) in 2002 played an important role in the development of research on the effects of light on living bodies. The role of non-image-forming vision in the sense of vision was clarified. Concretely, signals sent from the eyes to the suprachiasmatic nucleus in the brain were found to control the circadian rhythm of human physiological functions. This finding improved our understanding of the relationship between light and the circadian rhythm.

With the development of recent artificial light, light spectra started to attract attention in addition to two conventionally used factors that describe the quality of light, i.e., color and brightness. Unlike color itself, light spectra cannot be visually recognized by humans; however, the spectra provide an important factor for considering human-centric lighting in terms of the structure of human photoreceptors and the principle of vision.

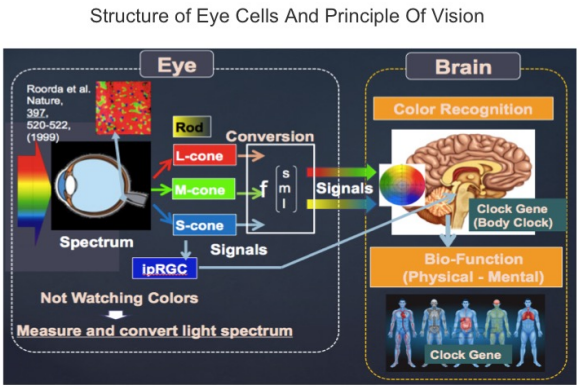

Figure 2

Figure 2 shows a schematic diagram of the structure of human photoreceptors and the principle of vision.

Three types of photoreceptors, rods, cones, and ipRGCs, exist in the eyeballs for detecting light. In dark environments, rods are highly sensitive to light but are not involved in the perception of color. In contrast, cones respond to bright light and are responsible for the recognition of color. Note that cones themselves do not perceive color; instead, short, medium, and long cones detect the intensity of light at their preferred wavelength. The signals detected by the cones are converted to two electrical signals, which are then sent to the visual association cortex in the brain to perceive color.

In other words, three signals obtained by the three types of cone are subjected to signal conversion, resulting in the perception of a certain color. Mathematically, there are some degrees of freedom in the combination of three light intensities. Therefore, it is considered that the same color temperature can be reproduced even using fluorescent and LED lights with different spectra, whose reproduced color is perceived as the same Figure 3.

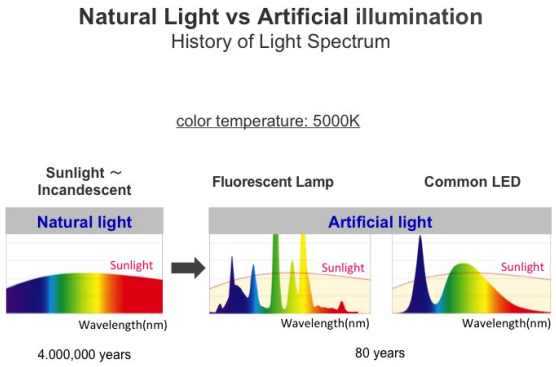

Figure 3

However, the intensity of light in a certain wavelength region more directly acts on ipRGCs, which contribute to the control of the circadian rhythm, than on the rods and cones; in other words, a difference in the spectrum has a significant meaning for ipRGCs.

On the basis of the above discussion, TRI-R spectrum technology, respecting the circadian rhythm and focusing on sunlight and its diurnal variation, has been developed for human-centric lighting. The technology is outlined in the next section.

TRI-R spectrum technology to realize human-centric lighting

Humans have evolved biologically under natural light over the past 4 million years. On the other hand,It was only 80 years ago that artificial light, such as fluorescent and LED light, was developed. This development significantly

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improved energy efficiency and contributed to society. However, as shown in Figure 3, there is a difference in the spectrum between natural light and artificial light, which cannot be recognized from the color of light. This difference, as well as the diversity of lifestyles of people today, led to the examination of human-centric lighting considering the effects of light on the circadian rhythm. As explained above, TRI-R spectrum technology is based on the spectrum of sunlight or black-body radiation. As shown in Figure 4(c), TRI-R spectrum technology focuses on natural light without excessive intensity peaks or the omission of a particular wavelength region.

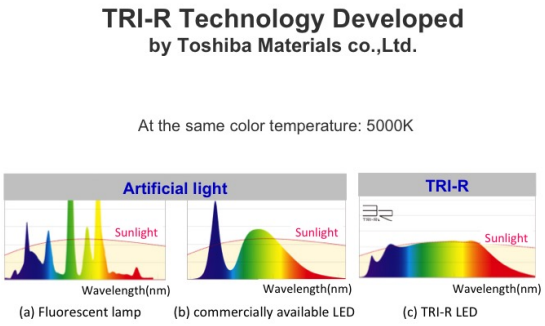

Figure 4

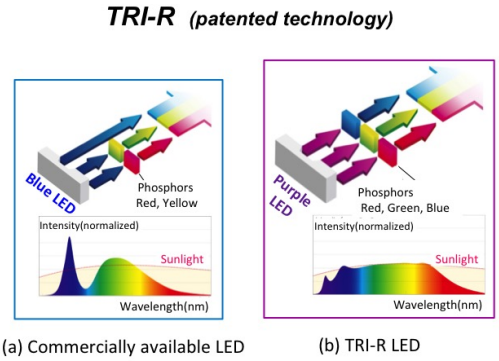

Figure 5

White light from commercial LEDs is realized by placing phosphors that emit yellow, green, and red light on top of a blue excitation layer (wavelength, 450–460 nm). In principle, the intensity peak in the spectrum of blue light tends to be generated by this method Figure 5(a).

In contrast, in the case of TRI-R spectrum technology, purple light with a wavelength in the range of 400–420 nm is used as the excitation light, most of which is consumed to induce the emission of visible light by phosphors. The obtained spectrum is continuous and designed to have a high spectral luminous sensitivity. The peak wavelength of emission from several phosphors and the compounding ratio that constitute the luminous layer are optimized. A color temperature in the range of 2000–6500 K is reproduced by changing the design of the luminous layer, covering almost every time zone of dawn till dusk in nature.

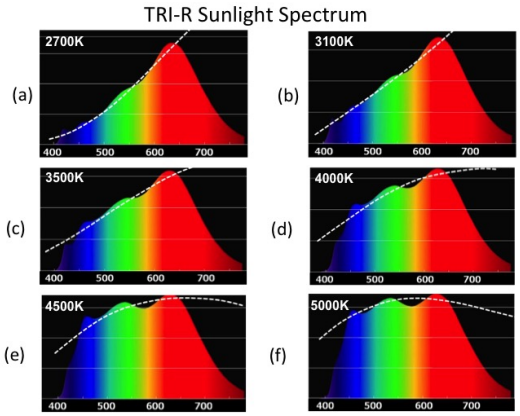

Figure 6

Figure 6 shows an example of a sunlight spectrum with a color temperature in the range of 2700–5000 K that is generally used in lighting devices. Currently, light sources using TRI-R spectrum technology are sold under the name of “Sunlike Series” by Seoul Semiconductor. Please refer to the website of Seoul Semiconductor for details.

Diurnal variation of sunlight as one of the factors in human-centric lighting

In modern society, light is used for various applications. The quality of the light used for different applications is developed in accordance with the purpose of its use. The verification of the effects of dynamic lighting on the people’s mood, sleep, alertness, concentration, and working performance has been ongoing at facilities for elderly people, elementary schools, and workplaces[7][8][9][10][11]. The underlying concept of this research field is a relationship between the circadian rhythm and light. Then, it is expected that the accuracy of verification tests and the analysis of test results will improve when the third parameter, the spectrum, is added to the two generally used parameters of brightness and

color. We will introduce the basic concept as well as the results of studies that have been carried out jointly with research centers affiliated with universities at the Symposium. Furthermore, we will also introduce a circadian lighting system as an advanced dynamic lighting system focusing on the diurnal variation of sunlight that has been developed to contribute to the advancement of future basic research and clinical trials.

References

[1] Brainard, G.C. et al. (2001). Action Spectrum for Melatonin Regulation in Humans: Evidence for a Novel Circadian Photoreceptor. Journal of Neuroscience 21, 6405–6412

[2] IARC Monographs Programme finds cancer hazards associated with shiftwork, painting and firefighting PRESS RELEASE N.180 5 December 2007

[3] Doi, M. et al. (2010). Salt-sensitive hypertension in circadian clock-deficient Cry-null mice involves dysregulated adrenal Hsd3b6. Nature Medicine 16, 67–74

[4] Karatsoreos, I.N. et al. (2011). Disruption of circadian clocks has ramifications for metabolism, brain, and behavior. PNAS 108, 1657–1662

[5] The Washington Post. Blue light from electronics disturbs sleep, especially for teenagers. September 1, 2014

[6] Financial Times. Safeguard eyesight by taking care over use of LED light. December 29, 2014

[7] Mott, M.S. et al. (2012). Illuminating the effects of dynamic lighting on student learning. SAGE Open April-June, 1–9

[8] Barkmann, C. et al. (2012). Applicability and efficacy of variable light in schools. Physiology and Behavior 105, 621–627

[9] Giménez, M.C. et al. (2017). Patient room lighting influences on sleep, appraisal and mood in hospitalized people. Journal of Sleep Research 26, 236–246

[10] Jensen, H.I. et al. (2016). Shift work and quality of sleep: effect of working in designed dynamic light. Int Arch Occup Environ Health 89, 49–61

[11] Mirjam, M. et al. (2017). Bright light delights: effects of daily light exposure on emotions, rest-activity cycles, sleep and melatonin secretion in severely demented patients. Current Alzheimer Research 14, 1063–1075

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LED Filaments – A new Technology Enables Classical Design in LED Retrofit Lamps

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Abstract

The technical progress of LEDs in the last years has enabled new luminaire designs in the General lighting market. Due to the increase of efficacy, less LEDs could be used and with the reduced thermal load, heatsink sizes could be minimized or heatsinks could be omitted at all. As a result the luminaires became smaller, thinner and less heavy.

In contrast to the luminaire world, LED retrofit lamps have a strictly defined form factor and there has always been a strong demand to achieve the same appearance as during the last one hundred years. However the first LED retrofit lamps had a quite different look compared to the “good old” incandescent bulbs. With the increase of LED efficacy, the bulky heatsinks disappeared and the LED bulbs looked more like their classical predecessors. But only with the development and continuous improvement of the LED Filaments, real incandescent look-alikes were possible.

One of the big technical challenges when using LED Filaments, is the thermal design. The main cooling path of an LED Filament lamp is going from the LED directly through the gas filling of the bulb. This requires a good understanding of the thermal situation and sophisticated measurement methods to determine the temperatures of the LED Filaments in the bulb.

Another challenge is the proper electrical driving of the LEDs. The Filaments are switched in different parallel — serial circuit configurations, depending on the input voltage and the targeted lumen output of the lamp. To ensure that the current does not spread inhomogeneously among the Filaments in parallel configurations the forward voltage of the LED Filaments must not differ too much.

The development of LED Filaments is still moving ahead. New upcoming designs allow to omit the usage of the gas filling and thus facilitate the manufacturing processes for LED Filament lamps. Other new developments of LED Filaments are targeted to provide decorative “new” lamp designs, like carbon filament lamps.

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A short recap of the history of LED Retrofit lamp development

In 2009 first LED retrofit lamps were launched in the market, which were more than just decorative lamps. At that time the LED efficacy has reached a level which made real 40 W replacement lamps possible. The appearance of these first replacement lamps was completely different from the appearance of their incandescent brothers: The Aluminum heatsink was quite big and bulky and the light was only emitted from the relatively small bulb on the top.

Figure 1: Left side: Lamp with a smooth heatsink using SMD LEDs, Right side: Lamp with LED Filaments.

In the following years the appearance of the LED lamps did not change too much. The heatsinks rather became bigger, as replacements for higher wattages — up to 100 W — had been developed. The rapid increase of the LED efficacy then triggered the increase of efficiency on LED lamp level and this allowed year by year a reduction of the heat sink size.

In parallel new LED types, so called LED Filaments, were developed. These LEDs made lamp designs possible, which looked like the traditional incandescent bulbs. The LED Filaments could be mounted in the existing mechanical environment, using processes and components from conventional lamp assembly. At the beginning these LED Filament lamps were mainly used for decorative applications, but step by step the performance of the LEDs and hence the performance of the lamps was improved. Today the LED Filaments lamps have made the step from decorative lighting to real lighting and are available in the same lumen packages and wattage equivalents as conventional LED lamps.

Figure 2: Picture of a DURIS®L.

LED Filament technology

General structure of the LED Filaments

A typical representative of an LED Filament is the DURIS®L. This LED Filament is available in various lumen packages up to 250 lm per Filament and various versions with different voltages.

It consists of a string of LED chips which are mounted on a substrate. The LED chips are connected in series by wire bonds. The basic principle for white light generation is the same as for standard SMD LEDs. For this reason the LED Filament is covered by a converter material to convert the blue light of the chips into white light. This material is applied both on the top side and the bottom side of the Filament, as it is an omni-directional LED emitting light to the top and the bottom. There are two contacts, one on each side of the Filament, which are designed to be connected by spot welding to the lamp wick.

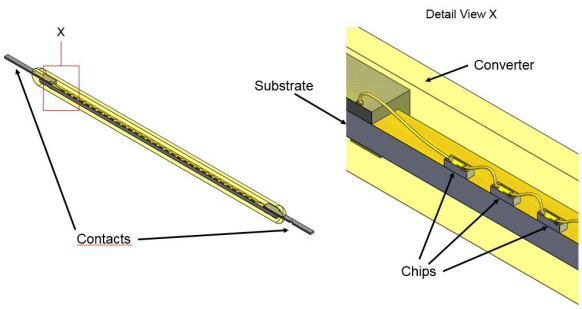

Figure 3: Cross section of an LED Filament (DURIS®L).

Thermal evaluation of LED Filaments in Retrofit bulbs

One of the challenges of LED Filaments is to keep the temperature of the LEDs inside of the glass bulb under control. As the LED filaments are just contacted by a small welding spot, the thermal load of the LEDs is mainly dissipated through the gas which is filled in the bulb. It is recommended to use a thermal conductive gas (e.g., Helium) to achieve optimum heat dissipation. The temperature of the LED Filament depends on the driving current, the number of Filaments in the lamps, the ambient temperature around the bulb and the bulb shape. The following simulated temperature distributions in two different lamps show the hottest temperatures directly at the LED Filaments and that the heat is transferred through the atmosphere in the bulb to the glass and then to the outside of the bulb.

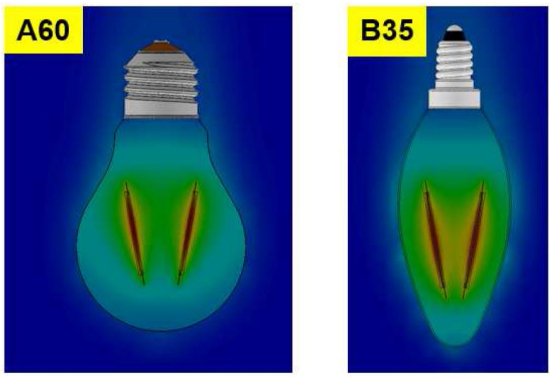

Figure 4: Temperature distribution in Filament lamps, simulated.

As it is not easy to measure the temperatures in a sealed bulb filled with a thermal conductive gas, it is important to have a good correlation between simulation results and measurement results of the LED Filaments.

The following tables show simulated temperatures and thermal resistances of a vertical oriented LED Filament in air and in helium at two different driving currents.

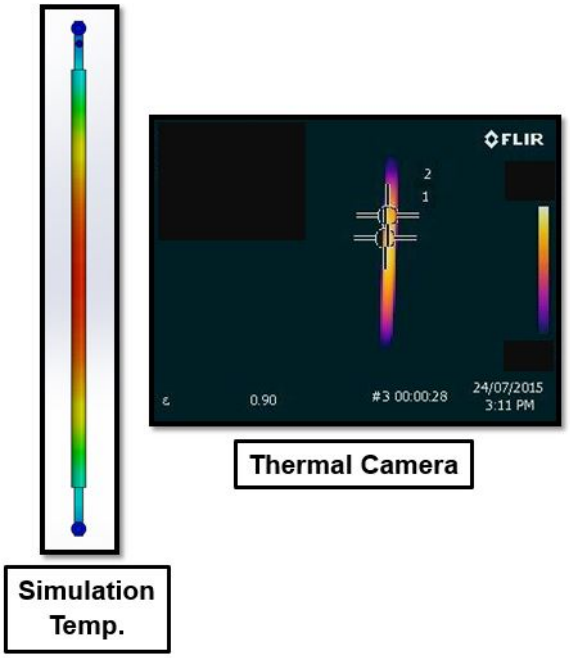

Figure 5: Simulated and measured temperatures on a single LED Filament.

Table 1: Results in Air.

AIR	If = 10 mA	If = 18 mA
Tj peak	130 °C	196 °C
Rth ja	101 K/W	91 K/W

Table 2: Results in Helium.

HELIUM	If = 10 mA	If = 18 mA
Tj peak	77 °C	111 °C
Rth ja	52 K/W	47 K/W

Simulation and measurement results show a significant reduction of LED temperature when operating the LED Filament in helium. The Junction temperature is roughly 1,7 times lower compared to the operation in air.

Electrical considerations of LED Filaments in Retrofit bulbs

Filament lamps are very well defined products and there is a limited number of variants for the lumen output. This is originating from the different wattages of incandescent lamps. Depending on the required lumen output, the number of LED Filaments per lamp varies, but normally there is only an even number of LED Filaments used. To

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build a 25 W equivalent bulb, 2 LED Filaments are sufficient and for a 100 W equivalent bulb up to 8 pcs LED Filaments are required. The LED Filaments then are switched in serial-parallel circuits. As long as the LEDs are only switched in series, each LED will be driven with the same current, which is provided from the driver circuit. As soon as the LEDs are switched in parallel, the total current from the LED driver will split on the different paralleled LED Filaments. Due to the differences in forward voltage of the different LED Filaments and the steep forward voltage characteristic, the current will split inhomogenously on the different LED Filaments. LEDs with a higher forward voltage will be driven with a lower current, while LEDs with a lower forward voltage will be driven at higher currents. Then this Filament with the higher current will get hotter than the others and the forward voltage of this Filament will be further reduced. This will lead to a further increase of current and temperature on this Filament. This can finally lead to an overheating of this Filament resulting in a reduced life time or in a spontaneous failure. This effect of thermal runaway is well known for LEDs in parallel circuits, but it is more critical in Filament bulbs due to the thermal situation.

A proper design is required to avoid the thermal runaway effect in parallel circuits. First it is important to have a tight forward voltage binning of the LED Filaments to minimize the forward voltage differences. Depending on the actual thermal situation inside of the bulb and on the actual forward voltage characteristics of the LED Filament, the LED driving current has to be chosen properly. In a parallel circuit the total LED current should be chosen to be so far below the maximum allowed driving current so that there is additional headroom for the inhomogeneous distribution of the current across the different LED Filaments.

Outlook on future developments of LED Filaments

The LED Filaments have reached a technically quite mature status, but there is further development ongoing. The DURIS®T is a new type of LED, which has a different construction compared to the LED filaments described before.

For this LED, the substrate is an aluminium based Metal core PCB. The LED chips are sitting on the top side and are covered by converter material only at the top side. In contrast to the LED filaments, the DURIS®T is not an omni-directional LED, it emits the light only to the top. There can be one or two strings of LED chips mounted on the substrate, which makes a device with two different colours possible. A use case for such a dual color LED is “Dim to warm”. Optionally there could be other components, like a resistor, assembled on the substrate.

The advantage of this design is that it is not necessary to fill the bulb with thermal conductive gas to dissipate the heat. It is enough to ensure a proper thermal contact of this LED in the area of the electrical contacts. By avoiding the gas filling, the whole assembly of the bulb can be simplified and plastic can be used as bulb material. Although the LEDs are not omni-directional any more, the complete bulbs still have an incandescent like appearance.

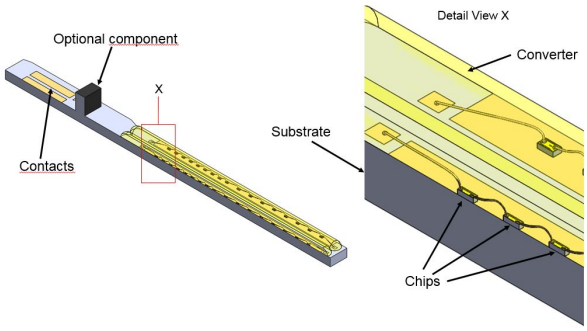

Figure 6: Cross section of a DURIS®T.

A different direction of development are the flexible LED Filament, where the LED chips are mounted on a flexible substrate. In this way new shapes of filaments can be formed in the bulb.

Figure 7: Lamp with a Flexible Filament.

Conclusions

The appearance of the first LED retrofit lamps was quite different from what consumers were used to. While incandescent or halogen bulbs were made out of glass, the LED retrofit lamps were bulky and had quite big heatsinks due to the necessity to dissipate the thermal load of these lamps. The consumer's wish for a familiar and traditional appearance of LED bulbs has triggered the development of LED Filaments and the progress in LED technology has finally enabled the development of incandescent look-alike lamps. In the first years, LED Filament lamps were decorative lamps, but today these lamps can cover the full range of incandescent lamps up to 100 W replacements.

When using LED Filaments, special care has to be taken about the thermal situation in the bulb. It is recommended to use a thermal conductive gas like Helium to ensure a proper heat dissipation. Another topics which has to be considered is the effect of thermal runaway when switching LED Filaments in parallel. A careful electrical design is necessary to avoid an overheating which could results in reduced life time or spontaneous failures.

However the development of LED Filaments has not ended yet: New products like Metal Core PCB based Filaments enable simpler assembly processes for the lamps. Flexible Filaments on the other hand allow completely new lamp designs and even the appearance of carbon filament lamps can be mimicked.

Acknowledgment

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References

[1] SOLERIQ®L38, Application Note, Ng Kok-Eng, Ch'ng Kar Siew, Lee Ee Lian, Lang Kurt-Juergen, Anuarul Ikhwan, Horst Varga, Eckert Tilman

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An Introduction of OLED Lighting Technology

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Abstract

Beside to display technology, OLED also has unlikely potential for lighting applications. Where extremely thin, flexible or transparent light sources are desired, OLED can exploit its potential as a supplement to the LED. The presentation will give a general introduction to the OLED technology and an overview of the market. Furthermore it will focus on current research topics and potential application areas.

The improvement of flexible OLED is currently the focus of worldwide research activities. Thin substrates of primarily barrier-coated polymer films, but also metal foils or ultra-thin glass, were tested for use in OLED production and have advantages and disadvantages. OLED prototypes on polymer substrates as well as ultra-bright glass were realized by Fraunhofer FEP. The main development areas are the improvement of device stability and brightness. This includes intensive work on encapsulation as well as the development of stacked OLED architectures on flexible substrates. In future, the focus will be on the development of integration solutions in functional devices and surfaces using established technologies.

Fraunhofer FEP works on processes along the entire value chain to produce flexible OLEDs in both, sheet-to-sheet and roll-to-roll processes.

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Introduction

Large, extremely thin, flexible and even transparent lighting and display modules — all these can be produced using organic light emitting diodes (OLEDs), see Figure 1. Arguably, these properties can be achieved using other technologies as well. It is the fact that OLEDs are surface emitting light sources that can even be segmented which make them truly unique. This is one of the reasons why the automotive and other industries show a strong interest in OLED technology.

Figure 1: World largest flexible R2R OLED.

A brief history of OLED

In the 1950s and 1960s fundamental research was conducted on the electroluminescence of organic compounds. With driving voltages of more than 300 Volts and low reliability these first crystal-based organic light sources could not be exploited commercially. Only when researchers started using thin amorphous organic layers in the 1980s organic optoelectronic devices started to become commercially viable. The first organic electroluminescent diode with two sublimed juxtaposed thin layers was made by a Kodak team in 1987. It consisted of the layers indium tin oxide (ITO) / diamine / AlQ3 / MgAg. While the outer two layers serve as electrodes, diamin is a hole transport molecule and AlQ3 is an electron transport molecule and a luminescent centre simultaneously. Shortly afterwards an electroluminescent diode using a conjugated polymer instead of the so called “small molecules” was invented. Both types are described by the general term “OLED”.

OLED technology — the Basics

Since the 1980s OLEDs are made from thin organic layers. The simplest device consists of an organic luminescent centre in-between two electrodes (see Figure 2). A potential applied to the electrodes leads to the injection of electrons and holes into the organic layer. Recombination of those pairs provides energy to an excitable molecule. Upon returning to its ground state this molecule can emit an electromagnetic radiation. A band gap in the energy range of visible light (provided by a conjugated electron system) and one or both transparent electrodes results in a light-emitting device that is named as follows: If the transparent electrode is the first layer on top of the substrate the resulting OLED is called “Bottom-emission”. If it is the last layer, therefore being on top of the organic layer, it is called “Top-emission”. Both electrodes being transparent gives a “transparent” OLED (overview see Figure 3).

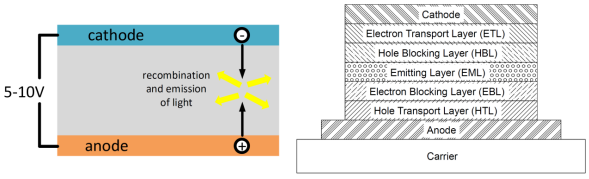

Figure 2: Simple OLED stack (left), typical OLED stack (right).

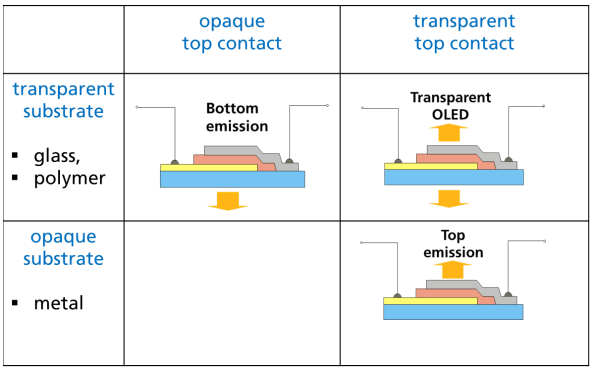

Figure 3: Overview types of OLED.

Today, an OLED has a much more complex structure (see Figure 1) to improve efficiency. Injection layers (EIL, HIL) reduce energy barriers between electrodes and the organic stack, resulting in a higher amount of charge carriers being introduced into the organic layers. Electron and hole transport layers (ETL, HTL) ensure an optimal mobility of both charge carriers. Finally to prevent charge carriers from moving from electrode to electrode without exciting a molecule,

blocking layers (EBL, HBL) provide a sufficient energy barrier. Figure 4 shows a simplified overview of the energetic positions of highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO).

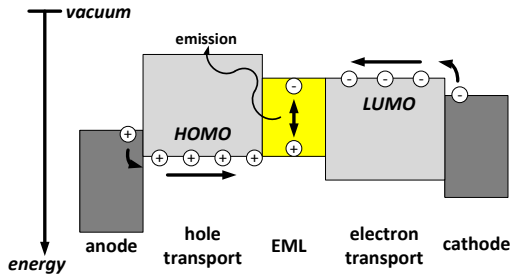

Figure 4: Overview types of OLED.

Technology and market today

Rigid or flexible? With glass or polymer encapsulation? Display or large-area lighting application? These questions are important in terms of technology and market aspects. Encapsulation of the organic materials is of utmost importance due to their lack of resistance against water and oxygen. Technologically, glass encapsulation has demonstrated OLEDs with a shelf-lifetime of more than 15 years. Although literature on shelf lifetimes of flexible OLEDs with a polymer-based barrier system is sparse, it can be estimated, that they do not show shelf lifetimes of more than 2 years due to the higher transmission rate of water vapor and oxygen through the barrier-coated polymer webs. This makes flexible barrier systems to a focus of current OLED research. While encapsulation and the OLED substrate divide technology and market into “flexible” and “rigid”, the substrate size and backplane technology divide the market again into “Display” and “Lighting”. Where displays need small pixel sizes, luminances of about 1000 cd/m^2 and a backplane to address each pixel, lighting applications need large-area OLEDs, they do not exhibit the need of a matrix-backplane but luminance requirements are higher ($> 5000\,\mathrm{cd/m^2}$).

This report will focus on the OLED lighting market, which is expected to be 2.5 billion USD in 2027 (for comparison: market for OLED displays is forecasted to be 57 billion USD in 2026). The market growth will however be very slow until 2019/2020 where the overall sales at panel level will remain below 200 million USD globally (source: IDTechEx 2018).

Today several companies produce for the OLED lighting market, among them are LG and OLEDWorks. Most of the products sold today are using rigid OLEDs targeting room lighting as well as automotive tail lights. Figure 5 shows examples for room lighting. Automotive OLEDs tail lights can be found in Audi A8, Mercedes Benz S-class and BMW M4 GTS amongst others.

Figure 5: OLED luminaires with rigid and flexible OLEDs.

The tables 1, 2 and 3 gives an overview of technological parameters of flexible and rigid OLEDs which are commercially available today and a selection of prices.

Table 1: Overview of available rigid OLEDs.

	active area [cm^2]	lum. eff. [lm/W]	lum. flux [lm]	lumi-nance [cd/m^2]	thick-ness [mm]
WHITE					
3000/4000*	10×10	90/75	75	3000	0.88
3000/4000*	20×5	90/75	75	3000	0.88
3000/4000*	40×5	90/75	150	3000	0.88
3000/4000*	30×10	90/75	230	3000	0.88
3000/4000*	D10	90/75	60	3000	0.88
3000**	10×10	75	300	8500	1.4
4000**	10×10	57	250	7000	1.4
4000**	22×4.5	50	100	3000	
3000***	8×8	40	60	3000	
AMBER					
**	8.8×2.5	50		2000	

* www.lgoledlight.com
** www.oledworks.com
*** www.kanekaoled.jp

OLED @ Fraunhofer FEP Dresden

An application-oriented research organization with competences that include more than 15 years of experience in covering the whole value chain of OLEDs and the similar process for OPD (organic photodiodes) — this is the Fraunhofer Institute for

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Table 2: Overview of flexible OLEDs.

	active area [cm^2]	lum. eff. [lm/W]	lum. flux [lm]	lumi-nance [cd/m^2]	thick-ness [mm]
WHITE					
3000/4000*	20×5	55/50	75	3000	0.41
3000/4000*	40×5	52/47	150	3000	0.41
3000/4000*	30×10	52/47	230	3000	0.41
3000/4000*	30×30	52/47	750	3000	0.41

* www.lgoledlight.com

Table 3: Overview of OLED Panel prices.

Module size [cm]	Product	lum. eff. [lm/W]	Price
22×4.5*	Keuka Module Promotion Kit	100	99$
12.7×12.7	Brite 2 Promotion Kit	300	199$ for 4 Modules
12.7×12.7	Brite 3 Promotion Kit	300	149$ for 3 Modules

* www.oledworks.com

Organic Electronics, Electron Beam and Plasma Technology (FEP) in Dresden. We offer solutions for miniature-OLEDs (Microdisplays) as well as large-scale-OLEDs for lighting applications, though some of the following services apply to large-scale OLEDs only. Flexible OLEDs are produced using Sheet-to-Sheet and Roll-to-Roll-processes. To start with the basics for OLED production and continue onto the complete devices: We provide support for equipment manufacturers to develop and optimize their tools for thermal evaporation, encapsulation and the other process steps. Customers can also test their materials (e.g., hole-transport material) in a complex device built by us. That includes comparison to existing solutions. We then offer customer specific OLED prototypes with all variations possible: Size, shape, color (tunable multi-color possible), flexible or on rigid glass, driving by microcontrollers and, of course, segmentation of the light-emitting area. An excellent example for these opportunities is our “Project Monarch”, which can be seen in the pictures Figure 6 and is also sold as a boxed set to customers interested in possessing such a colorful OLED for a moderate price. Furthermore, we offer integration solutions for OLEDs into textiles, be it in the shape of buttons, stripes or other. This ties in with our flexible OLEDs designed for wearables such as wristbands with added touch-sensor functionality.

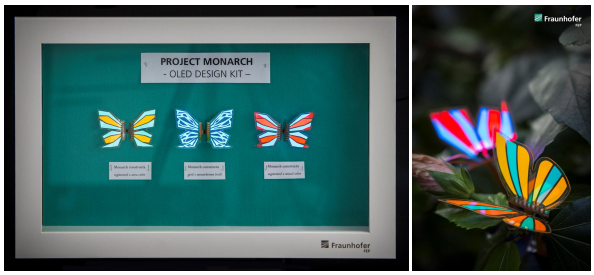

Figure 6: R&D samples of flexible OLEDs.

While our range of available solutions already is formidable, we constantly strive to improve our technology. Currently we are working on improving flexible OLEDs to be used in automotive tail lights. With some glass-encapsulated-OLED-based tail lights already available from manufacturers such as BMW, Audi and Mercedes, the heat management, lifetime and encapsulation still need to be improved for flexible high-luminance OLEDs. Rehau built a demonstrator in cooperation with us to show the potential of this emerging market (see Figure 7).

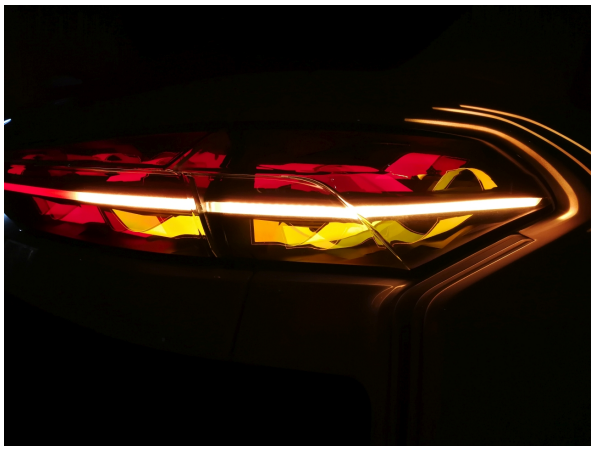

Figure 7: Rear light demonstrator with flexible OLEDs.

The future of OLED

As with most of the technologies in research, the future of OLED has potentials but also risks. To start with the risks and conclude with the multiple potentials: OLED technology is, despite more than ten years of development, still more expensive than other lighting technologies used today. If researchers are not successful in reducing the costs, the additional price has to be outweighed by technological advantages. In terms of displays these advantages are the high contrast and the saturated colors possible. But Micro-LED and QLED-technology might close that gap in the

near future. For lighting application the advantages are the surface emissivity and the possibility to divide the active, light-emitting area into segments that can be powered separately without the need of expensive backplane technology. While the first advantage might become accessible through edge coupled LEDs in a few years' time, the possibility of segmentation seems to be a factor that no other technology is going to possess in the foreseeable future.

The second risk is the need for improved reliability of flexible OLEDs. That includes the stability of the light-emitting materials as well as the barrier properties of the encapsulation. With a lot of research taking place on these topics, chances are that they will be solved in the next coming years.

Standing against the two risks is a variety of potentials. As mentioned before, the market for OLED lighting is expected to be 2.5 billion USD in 2027 (source: IDTechEx 2018). Table 4 gives an overview of lighting market segments available today and to evolve in the next years.

Table 4: Overview of market segments for OLED.

Market segment	Examples for OLED products
Signage	Buttons, Signs
Automotive lighting	Tail lights, Interior lighting
Room lighting	Luminaires
Others	Medical applications, Wearables

Most of the potentials can be shown using concept studies and prototypes already presented on conferences for the automotive lighting segment. Tail lights are to become ever more innovative and unique car elements as a way to distinguish one car from another. That includes 3D elements, possible through the use of flexible OLEDs (see lefthand Figure 8 (Audi, ISAL 2015)). The use of segmented OLEDs then allows for animated lighting and therefore gives the possibility of customer-individual welcome-animations.

Figure 8: Possible OLED applications for automotive from Audi.

From the concepts shown the main advantages of OLED technology are obvious: flexibility, surface-emissivity, segmentability, color-tunability, the possibility of transparent lighting modules and, on top of all that: the design freedom that derives from the other aspects.

Acknowledgment

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Special thanks to my colleagues, especially: Tobias Großer, André Philipp und Michael Törker,

References

[1] Hertel, Organische Leuchtdioden.
[2] F. Templier, OLED Microdisplays: Technology and Applications.

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The Latest Developments in Laser Light Sources For Industry-Leading Luminance

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Abstract

We provide an update on laser light technology including luminous flux, luminance and lumen density. LaserLight has demonstrated record breaking results with 1000 lumens emitted from a 350 micron diameter window, an order of magnitude higher than other solid state light sources. We describe recent, innovative laser light modules that produce highly directional and precisely shaped spotlight illumination. Novel laser light systems are described including dynamic modulation and waveguide delivered lighting. Lastly, actual results from implementations in lighting applications are illustrated.

The paper and presentation address:

- Introduction to laser light technology (laser diode pumped phosphor technology)
- Fundamental performance differences for laser light versus LED and legacy light sources including: lack of droop, order of magnitude higher luminance and lumen density, 2 degree beam angle, and efficient waveguide delivery
- Newest applications in architectural, entertainment and other specialty lighting

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Introduction to Laser Light

Legacy light sources such as halogen and metal halide produce highly collimated directional beams, but with short life and lower efficiency than LED sources. LEDs are highly efficient and long lasting, but encounter challenges at creating beam angles below 10 degrees with small optics.

Laser diode-pumped phosphor light sources utilize a high-power blue InGaN laser diode to excite a very small phosphor target — about 300 to 350 microns in diameter. The phosphor converts the laser light to broad-spectrum, incoherent white light, eliminating laser eye-safety risk. The small phosphor spot size allows for greater optical control of the down-converted white light emission. As a result, extremely narrow beam angles can be created, as small as 2 degrees with 1 in. diameter optics. The resulting sources are the smallest and most intense solid-state light sources commercialized for lighting applications, with luminance that is up to 10× that of the brightest LEDs. Laser diodes (LDs) do not suffer efficacy droop in the way that LEDs do. InGaN laser diodes based on semi-polar orientations of GaN operate at 3× to 5× higher gain compared to more conventional c-plane InGaN LDs.

This ultrahigh luminance then enables high-efficiency waveguide delivery, sharp patterns with high contrast from small optics and spatially dynamic light projection.

Specialty lighting applications that make use of very tight beam angles include entertainment and architectural lighting and are some of the most established users of halogen and high-intensity discharge (HID) light sources. Outdoor applications including street lighting and stadium lighting utilize very high-luminance sources like HID in order to optically control the light to achieve a complex illuminance pattern on the roadway or stadium grounds while maintaining a manageably small luminaire size. Specialty lighting applications like vehicle forward lighting and projection displays aim to achieve long illuminance throw, precise beam shaping and spatial beam modulation, and have historically applied HID technology to a great extent. LEDs have been adopted by all of these applications to some degree, and offer their well-known benefits of small form factor, reliability and luminous efficacy, but are not able to be utilized in high-luminance applications.

After significant development time, both HID and LEDs are limited from the standpoint of luminance. Development of Xenon HID light sources for automotive and entertainment lighting applications have reached luminance values [1]. of 1.5×10^8 cd/m^2, or for reference, approximately 1000 lumens from an arc size of a couple of millimeters in diameter, although the overall size of HID lighting systems is much larger. Despite their luminous efficacy, LEDs offer luminance somewhat less than the HID example above, because efficiency droop with increasing drive power also presents a fundamental challenge for LEDs to achieve higher luminance. As a new solid-state, high-luminance light source, laser light technology has now demonstrated luminance higher than 1.0×10^9 cd/m^2, or more than six times the highest HID.

Laser Light Source Technology

By fabricating a blue laser diodes on semi-polar orientation Gallium Nitride (GaN), blue laser light is produced at high levels of optical output power of 3 watts and more due to the high gain in the device. As importantly, these laser diodes show minimal droop characteristics, meaning that, for the first time, high power lasers with very small scale are being implemented in specialty lighting applications. Unlike a blue LED that emits a few watts of diffuse optical energy per square millimeter, several watts of light produced from the laser diode emanate from a light emitting area only tens of microns in width, and can therefore illuminate a tiny spot that is hundreds of microns in diameter.

To complete the spectrum for white light illumination, the blue radiation is partially converted to longer wavelengths by a phosphor element. Innovations in high temperature phosphors and special binding materials have enabled phosphors to convert light efficiently at the elevated power densities and temperatures that result from the laser light architecture. Two implementations of laser light have been developed that both achieve high luminance of more than 500 lumens from an emission diameter of 300 to 350 microns.

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Product Implementations

The first implementation of laser light discussed here is composed of a blue laser module that uses a fiber optic of 30 cm up to 10.000 cm of length to transport the blue light to the end where the light illuminates the phosphor element.

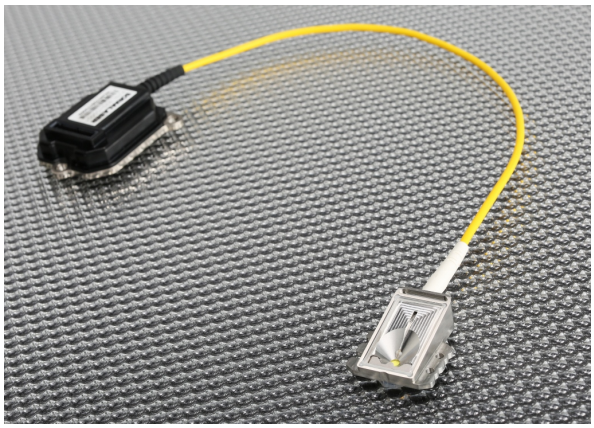

Figure 1: Blue Laser Fiber Module with Phosphor at Distal End.

Typical optical fiber carrying laser radiation operates at a transport efficiency of approximately 99.8 per cent per meter thus losses are very small even for significant fiber lengths. In contrast to other solid state light sources, the phosphor is operated as a reflecting element. This placement offers the advantage of straightforward heat sinking of the phosphor element which is important due to the high levels of power density. Reflectance from the phosphor also enables the configuration of safeguards on the emission of blue collimated laser light. Reflected light is blocked by beam blocks which can ensure that blue collimated laser light is never released. Additional safety and performance monitoring features are included in the blue laser module, where the optical output power and temperature of the high power blue laser diode are actively monitored with detectors. With this arrangement, the white light emitting element may be sealed in a location remote from the laser and its electronics which may be placed in another location that has more favorable physical and thermal characteristics. An example of a high luminance laser light fiber module is shown in Fig. 1.

In the second implementation of laser light, the phosphor element is placed in close proximity to the laser diodes, resulting in a fully integrated surface mount device (SMD) of 7 millimeter square dimensions.

As with the laser light fiber module, the phosphor is operated as a reflecting element. In each of the two configurations, about 500 lumens is emitted from a light emitting area only 300 to 350 microns in diameter resulting in luminance levels in excess of 1000 Mcd/m^2. Efficacy of the light output also remains roughly constant as power is driven higher due to the low efficiency droop of the lasers with increasing power. An example of the laser light SMD is shown in Fig. 2.

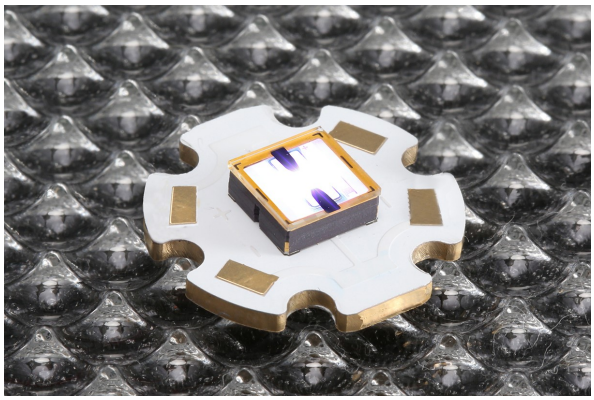

Figure 2: SMD Laser Light Component.

Integration of laser light sources

Enabling beam range of longer than 300 meters, and beam angles smaller than 8 to 10 degrees from 25 to 50 mm optic diameter has been challenging with conventional light sources. Utilizing laser light sources, beam distance of 1 km and beam angles of 2 degrees have been demonstrated with optics of less than 30 mm in diameter, well within convenient lighting system form factor. For existing optical systems that seek to maintain the same beam angle, the optics used may be designed to be smaller, lighter and have sharper beam geometries. Since laser light approximates a point source, laser light is well suited for diffractive optical elements for beam shaping. For example, a light shaping diffuser element can transform the output beam of a 1 degree spotlight module to a rectangle of 1 degree by 10 degree with efficiency higher than 92 per cent. Moreover, MEMS and liquid crystal lens technology can be added downstream from laser light modules in order to electronically control and dynamically change the beam angle and/or shape (Ref. 2,3).

The electrical and thermal infrastructure required for laser light match those already established for solid-state lighting. Laser light is a current driven

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system with very flat voltage characteristics, thus the electronic drivers control amperage with high accuracy and stability while disallowing voltage runaway and spikes. Like other solid state devices, the light output of laser light attenuates with increasing temperature, and so heatsinks are required to efficiently transport several watts of thermal energy away from each device.

Implementations of Laser Light

For ease of implementation, laser light technology is integrated into light modules. At the heart of the module is the 7 $\times$ 7 mm LaserLight SMD light source component delivering about 1000 Mcd/m^2 of luminance from a 0.35 mm spot size. Coupled with a TIR optic, the narrow beam is capable of illuminating at a throw distance of up to 1 kilometer.

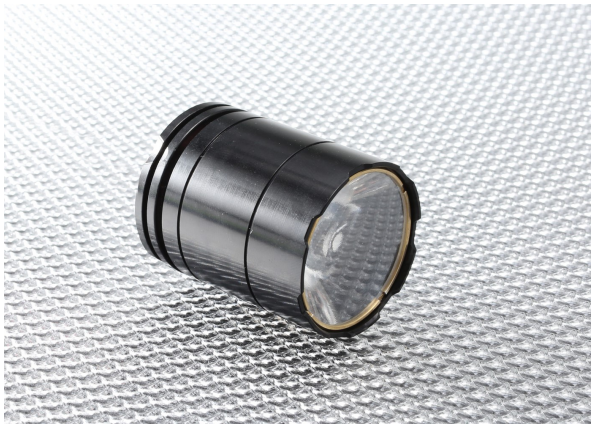

Figure 3: Compact Spot Light Module with Laser Light SMD Source.

This level of performance enables search and rescue lights with great range mounted on helicopters for example. Hand held illumination systems and those on vehicles can visualize objects at 1 km, a valuable capability at high speeds. When light is collimated to very narrow angle in this way, complementary optics are enabled at a high level of performance. For example, holographic diffusers may be applied that shape the beam up to 60:1 form factor and liquid crystal lens technology enables the beam to change its size dynamically. Each of these optical modifications perform at higher levels when paired with more organized light propagation like that which emanates from a laser light source and very narrow optics.

Other examples of spot light applications include

Figure 4: Track Mounted Spot Light with Laser Light SMD.

a track mounted architectural fixture that has a very narrow beam angle of less than 2.5 degrees with high uniformity and sharp cutoff. With a very narrow beam, fixtures may be placed farther away and still have precise lighting effects.

Figure 5: Vehicle Aftermarket Spot Light with Four Clustered Laser Light SMD With Optics.

Laser light components may be clustered together to generate more lighting power. Four sources are combined to make an automotive aftermarket lighting assembly implementing SMDs in a cluster with secondary optics. This very powerful and narrow beam fixture highlights how laser light extends performance capabilities in automotive applications alongside to those in architectural and portable lighting.

Architectural and entertainment lighting show similar designs and requirements as shown by a moving head fixture with five laser light sources to create a very narrow and powerful beam. The fixture is controllable in two axes using DMX standard protocol. The fixture can be applied

Figure 6: Moving Head Light with Clustered Laser Light SMD With Optics.

equally to entertainment or variable architectural needs.

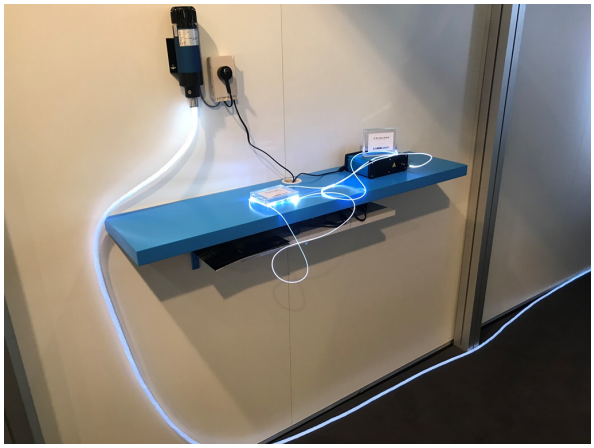

Figure 7: Fiber Optic Lighting Implementing Laser Light Sources.

Additional capabilities of high luminance laser lighting sources are applications of laser light based fiber optic lighting. Fiber optic lighting systems are used in various architectural lighting applications where it is important to have the light source and its electronics remote from the output surface. This approach is used when service of the light output location may be inconvenient, costly or unsafe like in very high or underwater locations. Decorative architectural applications can use illuminated, light scattering fiber to create very continuous light strips that highlight building elements. The high luminance of laser light enables the transport of light at high efficiency through very thin fibers as small as 1.5 mm in diameter.

Conclusions

Laser lighting technology has grown more mainstream in automotive applications which were the first to harness its high luminance characteristics in forward lighting like high beam. With new designs to increase performance and user friendliness, laser lighting is attracting significant interest in the architectural lighting marketplace and in specialty applications. Many system demonstrations have been proven as shown above and will ramp to production in the coming year. Development is ongoing to integrate directional white-light laser sources into next-generation lighting applications such as smart lighting, LiFi (light-based wireless data transmission), and the Internet of Things (IoT).

References

[1] 11th International Symposium on Automotive Lighting — ISAL 2015 — Proceedings of the Conference: Volume 16

[2] “SoraaLaser Introduces Dynamic Laser Light Source Technology For Specialty Lighting”, Photonics Online, May 3, 2017

[3] J. Carey, P Rudy, Laser Light Source Delivers Superior Optical Control, Photonics Spectra, November 2017

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Linear LED Strip Based on a High Frequency Design

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Abstract

Based on a high frequency model, a new technology for operating a linear LED strip is described. The electrical supply for the individual LEDs takes place contactless via a capacitive coupling. The required capacitors are formed by a pixel-structure of the copper strip line and the flexible printed circuit board as dielectric material. Subsequently, the application possibilities of such a design of a LED strip are discussed. Lumen output of groups of two or more LEDs can be separately controlled only by changing the frequency of the supply. This allows easy designs for applications like Human Centric Lighting or Horticulture Lighting. Moreover, several ways are described how such a LED strip can be dimmed to the per thousand range.

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State of technology

Linear LED strips have found a variety of applications in general lighting and industrial lighting. Almost exclusively, these are constant voltage versions for 12 VDC or 24 VDC. Such a LED strip is made up of a large number of identical designed segments with a typical length of 50 mm. These segments are connected in parallel and are each supplied with the constant operating voltage of the LED strip. Each segment usually has six to seven LEDs (Figure 1). This allows linear lighting applications to be realized with convincing flexibility: long light paths can be designed with one energy feed-in, and the LED strip can be waved and adapted to different geometrical situations.

Figure 1: Design of a LED strip with constant voltage.

There are two different models for the electronic design of such LED strips [1]:

- In the controlled design, the LED current of a segment is kept constant by means of a current controller to a default value. Such LED strips are characterized by the fact that a constant luminous flux over the entire length is ensured.
- Alternatively, the LED current of each segment may be determined by an electrical resistance. Such LED strips are simple and inexpensive. However, the luminous flux decreases gradually over the length, since there is no current control. [9]

The limitations of such LED strips are in the following areas:

- Through the current control or current drive, electrical losses occur. Here is to be expected with a control voltage drop of about 3 V. These losses are independent of the efficiency of the LEDs.
- The total achievable length of an LED strip is limited by the voltage drop of the parallel-connected segments.
- Dimming of such an LED strip is done by pulse-width modulation. This switches the power supply on and off with a typical switching frequency of 100 Hz to 1 kHz. Thus, the light output of such LED strips is not suitable for video. There are also increasing concerns about medical side effects caused by this mid-range flicker. [8][5][6]

A particular embodiment of such LED strips are those for lighting with “tunable white”. The color temperature of the day cycle is simulated by the mixture of two groups of LEDs with different color temperatures. For this purpose, two separate channels must be provided on a LED strip, which significantly increases the complexity of the layout. In practice, this has the effect that the achievable length of an LED strip is additionally reduced.

Possibilities of improvements

Basically, there are three ways to reduce the described limitation of LED strips:

- Using high-efficiency LEDs: This increases the efficiency of the LED strip. The losses due to the current regulation remain upright.
- Use of flexible printed circuit boards with the thickest possible copper coating: This reduces the voltage drop due to the flow of current along the individual segments. Those the possible length of the LED strip is increased. However, the total efficiency of the LED strip increases only insignificantly.
- With constant current design: a fundamentally different electrical design of an LED strip is realized. For this purpose, the parallel-connected LED segments are supplied with a constant current. In order to achieve the most uniform possible voltage distribution, as many LEDs as possible are connected in series per segment. The efficiency of such an LED strip improves significantly, since the losses of the current control per segment are omitted. Similarly, the dimming of such a design is thereby improved decisively. However, the

cost-attractive and unproblematic 24 VDC voltage system is abandoned.

Models based on a power supply with high frequency

In the described environment of the operation of LED strips, the authors have set the task to go a completely different way: The supply of the LED strip with high frequency and the supply of the individual LEDs contactless by an inductive or capacitive coupling.

The high-frequency power supply has the advantage that

- the ohmic losses of the segments are no longer determinative of the operation of the LED strip.
- It no longer counts the thickness of the copper available for the power line, but rather the area of the surface.
- As a result of contactless coupling of the LED, the required layout can be kept simple and the available surface area maximized.

The inductive model for the coupling of the LEDs was discarded, since it would lead to unmanageable EMC problems in practical use. Likewise, electrically conductive material or foreign bodies in the immediate vicinity of the LED strip would influence the inductive coupling.

The capacitive model for the coupling of the LEDs, can expect many advantages for the operation of the LED strip:

- The required capacities for the coupling of the individual LEDs should be made possible by a simple layout of a double sided copper coated flexible printed circuit board.
- This forms the high-frequency electric field inside the circuit board. An influence from the outside is therefore practically impossible.
- The circuit of LED and individually assigned capacitor can be tuned so that a selective operation of each LED would be possible in principle.
- In particular, each LED is supplied with a direct current, whereby the efficiency of the Constant Current design becomes fully effective.
- Each individual LED, with its individual wiring, forms an independent light element, so that the LED strip can be separated at any point.

Details on the structure of the capacitive model

The structure of the system is based on two transmission capacities, which the AC voltage generated by the transmitter is from the underside of the PCB to the top. One of these two capacities forms the forward line, the other the ground return line.

On the underside of the flexible circuit board, two continuous copper tracks are provided. On top of each two pixel-shaped areas are then formed LEDs, which each form a capacitor with the tracks of the bottom. The material of the circuit board is used as a dielectric for these capacitors. With a pixel size of 4 $\times$ 8 mm, this results in a calculated capacity of 20 pF.

The printed circuit board used is the flexible PCB commonly used for linear LED strips: base material polyimide with a thickness of 50 µm, printed circuit board structure 100 µm, double-printed solder mask as surface insulator. Holes of the flexible PCB are not required. Terminal solder points and two conductor strips on the underside represent the primary side for the RF feed. Between each of these two capacitors is a LED with its individual wiring of rectifier and capacitor (Figure 2).

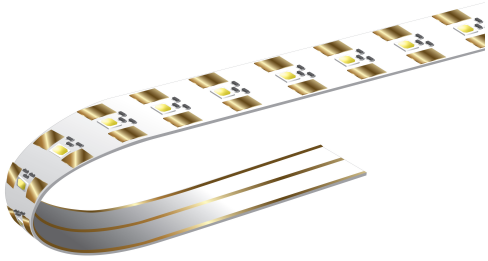

Figure 2: Design of a capacitive LED module.

On the transmitter side, an alternating voltage in the MHz range is generated by means of a series resonance converter and transmitted by means of power driver (full bridge) via the inductance L to the capacitances for the LED coupling.

For the operation of the LED, a DC voltage is required, which can be generated from the

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high-frequency AC voltage of the primary side (Figure 3).

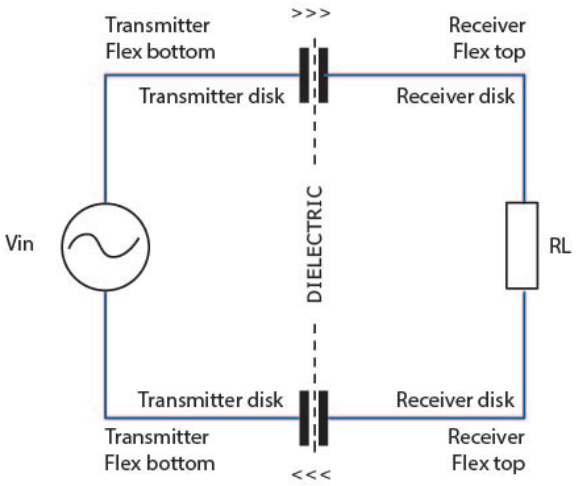

Figure 3: Principle of a capacitive LED module.

The voltage obtained should be as constant as possible. For this purpose, a two-way rectifier is used, wherein the center of the two capacitors forms the reference potential. The other side of the secondary plates is merged via two serially connected diodes, forming the other pole of the DC voltage (see Figure 4). The diodes alternately conduct the current to the positive or negative side. So there are no gaps as in the one-way rectification.

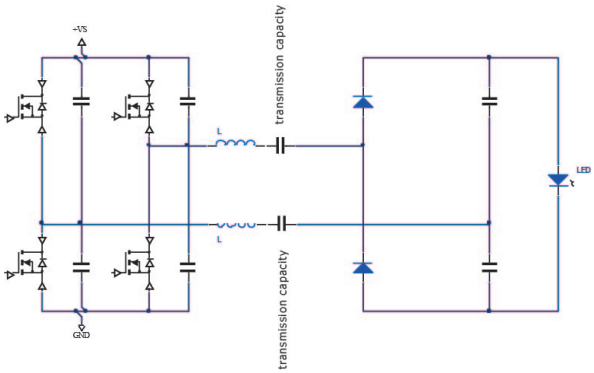

Figure 4: Details to the capacity model.

Dimming the LEDs in the capacitive model

For dimming the LEDs in the capacitive model, there are several possibilities:

1. **Amplitude control:** Therefore, the amplitude of the HF feed is reduced. As a result, this reduces the charging of the capacitances of the couplings and so the current flowing through the LED.
2. **Pulse group control:** Individual pulses of the HF supply are suppressed. This also leads to a reduction of the charging of the coupling capacity.
3. **Frequency control:** For this purpose, the frequency is changed, thereby influencing the resonance coupling of the individual LEDs. This also leads to a reduction in the current flowing through the LEDs.
4. **PWM:** The RF feed is switched on and off.

The methods one to three have the advantage that they act in very fine steps. Thus, a dimming up to the per thousand range is possible.

Measurements on a prototype

An experimental design was set up to evaluate the function of the capacitive model.

For this purpose, a segment of 9 LEDs (OSRAM DURIS E2835, $I_{f\,max}$ 120 mA, $V_{f\,max}$ 3.3 V) was set up. The flexible PCB has a width of 10 mm. For rectification a double diode (NXP PMBD700, V_{RRM} 100 V, I_f 125 mA, 4 ns) was used. As operating capacitors two ceramic capacitors with 1 µF / 50 V BF0603 were used. This structure can been seen in Figure 5. It is controlled by a frequency-controlled transmitter with a center frequency of 5.4 MHz and an output voltage of 106 V_{pp}.

Figure 5: Experimental design.

Under these conditions, the LEDs have a current of 70 mA with little ripple. The entire segment therefore requires 630 mA. If this segment is disconnected at any point, there will be no change in the operation of the remaining LEDs.

Summary and Outlook

It was shown that a high-frequency power supply in combination with contactless coupling of the individual LEDs is possible on the basis of the PCBs used for linear LED strips. In addition a capacitive model was used.

This results in the following advantages for a linear LED strip for conventional applications:

- Regulated DC operation of the LEDs without controller losses.
- Stepless dimming of the LED strip down to the per thousand range.
- Simple and cost-attractive design of a LED strip with the possibility of separating the LED strip after every single LED.

An entirely new dimension for the operation of a linear LED strip results from the possibilities of selective tuning of the individual LEDs on their individual resonant circuit: By changing the frequency of the feed of the LED strip, the current can be determined directly by an individual LED. Thus, subsequently groups of LEDs can be determined, which can be controlled from the outside in their light output. All without — as usual today — having to design a separate channel on the layout of the PCB. If two groups of LEDs are formed in this way, you can design a linear LED strip with tunable white for applications in human-centric lighting. But it is also possible that three or more groups can be formed on such a LED strip. This provides solutions for a variety of applications where a detailed spectrum design based on the interaction of multiple LEDs is required. A typical example are applications in the field of plant lighting. And all this in a Constant-Current-Mode with the possibility of dimming up to the per thousand range.

References

[1] BILTON International GmbH `http://www.biltongroup.com`

[2] Andreas Berger, *Drahtlose Energieübertragung Stand der Forschung, Applikationen, Trends* [german] from *Energietage 2016 "Innovative Technologien für zukunftsfähige Energienetze"* *http://www.ak-energie.at/pdf/ET2016/ET2016-6_Andreas\%20Berger_Drahtlose\%20Energie\%C3\%BCbertragung.pdf, September 26, 2016*, Energietag 2016, Wien, 2016.

[3] Mitchell Kline, *Capacitive Power Transfer* in *Technical Report No. UCB/EECS-2010-155, December 15, 2010*, Berkeley, 2017.

[4] Ben Minnaert, Nobby Stevens, *Optimal Analytical Solution for a Capacitive Wireless Power Transfer System with One Transmitter and Two Receivers* in *Energies, September 19, 2017*, Belgium, 2017.

[5] M. Poplawski and N. J. Miller. *Exploring Flicker in SSL: What you might find, and how to deal with it*, Chicago, ArchLED'11, 2011.

[6] M. Poplawski and N. J. Miller, *Exploring flicker in Solid-State Lighting: What you might find, and how to deal with it* in *Illuminating Engineering Society Annual Conference, November 1, 2011*, Austin, Texas, 2011.

[7] Peter Wambsganß, Nejila Parspour, *Kontaktlose Energieübertragung* [german] from `https://www.researchgate.net/publication/228413506_Kontaktlose_Energieubertragung`,Germany, May 2015 [Access on 05.06.2018]

[8] A. Wilkins, J. Veitch and B. Lehman *LED Light Flicker and Potential Health Concerns: IEEE Standard PAR1789 Update.* in *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, Atlanta, GA, 2010.

[9] ZVEI – Zentralverband Elektrotechnikund Elektronikindustrie e.V., Februar 2014.[Online] Available: `https://www.licht.de/fileadmin/Publikationen_Downloads/ZVEI-Schriften/1410_ZVEI_Schrift_LED_Dimmen.pdf` [german] [Access on 01.07.2018]

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Defining the Spectrum for Your Unique Lighting Application – Spectrum, TM-30-15, and Human Centric LED Sources

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Abstract

Today's novel, new LEDs spectrums and CCT tunable LEDs require more complex methods for characterizing "quality of light." Too many lighting specifiers today struggle with a supply chain using legacy specification methodologies, like simply CCT and CRI (Ra), derived from over a century of conventional bulb technology. As we close the door on traditional bulb use, new LED lighting technology offers beautiful options which require our industry to leave behind today's lingering, outdated standards such as ANSI bins and CRI. Tunable light sources enable users to create unique environments and to match seasonal or time of day illumination. Innovative phosphor blends, pumped by violet, blue, and cyan, are creating new spectrums never seen before, where whites are whiter, colors are richer, and efficacies are saving even more energy. Chromaticity targets can be targeted above or below the black body locuc (BBL), and spectrums can be tuned to match our growing understanding of human photobiological needs as well as the needs of the various plants and livestock. Merchandise in retail stores can look even more appealing, pedestrians can feel safer, patients can heal faster, and workers can be more productive. There are challenges in how to specify these innovative new LED sources. This talk will explore some of these new LEDs and review how new standards, such as TM-30-15, CQS, PAR, PPF, melanopic ratios, and GAIare struggling to keep up with the rapidly evolving industry.

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3 Stages of LED Lighting: From “blue and spotty” to “Just like the usual bulbs” to new lightning like never before

LED illumination has finally reached the stage where the industry can take full advantage of the benefits, flexibility, IoT-ization and customization enabled by today’s LED technology. In the first stage of LED lighting, roughly 10 years ago, the industry was struggling to reach ever higher efficacy targets, and the bulbs and luminaires being produced suffered from blue-tinted, spotty, glare-ridden, and low color rendering issues which turned off a wide range of end users in various applications. More recently, in the past 3–4 years, LED bulbs and luminaires began adhering to higher standards and produced warm, efficient, dimmable, high color rendering, and generally pleasant illumination sources which gained wide acceptance and adoption, essentially eliminating incumbent bulb technologies both indoors and outdoors. In that second phase of LED illumination, specifiers, manufacturers, and even consumers became accustomed to using CCT and CRI as the primary metrics for characterizing white LED light sources.

Today, in the third phase, the industry is moving in two very different directions. One is a cost driven direction, where lumen maintenance is targeted for around 6000 hours and quality of light is sacrificed. The example of this is the sub-one-dollar A19 bulb without any CRI listed (because it’s below 80) and no energy star or lighting facts label. Some of the world’s largest lighting companies are taking this direction for consumer solutions. This disturbing trend threatens to destroy the end-user confidence in LEDs that has been built up during the second stage. I urge the audience to avoid falling into that trap.

The other direction of the third stage is the exciting one which is the focus of this paper, where LEDs are creating lighting that feels natural and healthy to humans. Luminaires are taking on shapes and form factors never before imagined, and IoT connectivity brings flexibility, sensors bring adaptablility, and lighting brings new experiences which humans have never seen before. This lighting is beautiful, effortless for the user, feels good, and provides exactly the spectrum and illuminance needed in each particular application, environment, and time of day.

How CCT and CRI lose their meaning

Warm CCT LED sources with chromaticity slightly below the BBL have gained huge popularity in recent years, especially in retail shop lighting, where clothes need to look clean, colorful, and have “sparkle” to attract the shopper’s eye. Going below the BBL with LED sources is desirable mainly to match the human perception of pure white which goes below the BBL in the warmer CCTs (below 4000 K). In contrast, going above the BBL produces greenish and yellow-ish tint, which is quite ugly and makes people feel uncomfortable. A typical below BBL light source would be 3000 K or 3500 K with 80 or 90 CRI and with chromaticity targets located somewhere around the bottom of the ANSI bin or slightly below it. Some LEDs in this category have made use of short wavelength violet LED chips pumping blue, green, and red phosphors. While they are quite popular and claim “crisp” or “like-sunlight” results, some end users are turned off by the low efficacy and presence of potentially harmful near UV wavelengths.

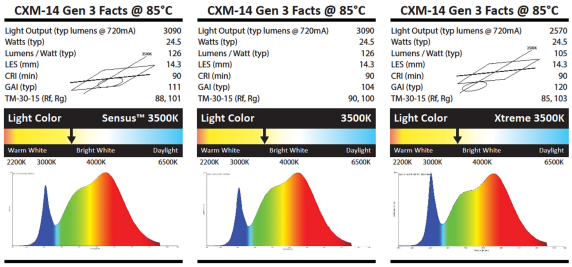

Figure 1: Comparing 3500 K 90 CRI sources on and below the BBL.

Figure 2: Comparing whites, reds, and blues under above 3 LED sources.

If you want to avoid exposing your merchandise to

near UV radiation, there are several LED options on the market which are below the BBL and use efficient royal blue LED chips with special phosphor blends to take the chromaticity below the BBL and match the human perception of pure white at 3000 K or 3500 K. An example of these are the Luminus Sensus^{TM} COB product lines. The Sensus product is a more practical approach to create pure whites and rich, saturated colors without sacrificing efficacy. These sources render the CRI metric essentially useless, as their actual color rendering capability is vastly better than similarly rated sources which are on the BBL. As an example, the image in figure 2 shows three 3500 K 90 CRI sources with distinctly different color rendering capability. The light in the center is on the BBL, while the "Sensus" light on the left is slightly below BBL on the bottom edge of the ANSI bin, and the one on the right is "Xtreme Sensus" with chromaticity coordinates just below the ANSI bin. While colors are hard to reproduce accurately with cameras, digital file formats, projectors, and printers, you can still see the different white, red, and blue colors in the image of these 3 sources. With the center source, on the BBL, you see the slightly yellowish hue, which is typical of a warm CCT, while the whites become more pure white as you move further below the BBL. Of course, if you move too far below the BBL, you will see pink-ish tones, like you see with supermarket meat lights in Europe. With the Sensus sources, reds also become less orange and even become a more vibrant cherry red further below the BBL. Even the blue jeans go from being "dirty" in the faded areas with the on-BBL source, to being more "clean" and "pure blue" with the below BBL sources. These 3 lights all have the same CCT and CRI values, but the lighting effect is dramatically different between the three.

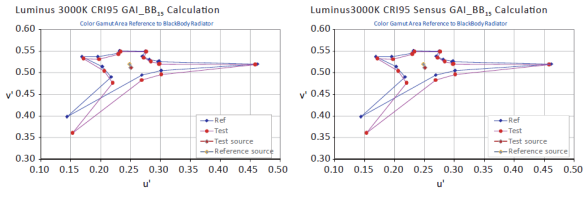

Figure 3: Gamut Area Index (GAI BB15) example plots.

TM-30-15, GAI, Red Chroma and Spectrum

With CRI and CCT essentially no longer useful for distinguishing differences between these sources, one might turn to TM-30-15 or Gamut Area Index (GAI) to characterize the visual differences. Again, comparing these three sources, the TM-30-15 scores are not vastly different, and thus are not useful for identifying visual differences. One of the challenges with TM-30-15 is that the Rf (fidelity) and Rg (gamut) scores are averaged over 99 color points, and thus the scores of the critical, more difficult colors like saturated reds, are "washed out" by the dozens of other faded/pastel color samples which are relatively "easy" for LEDs sources to score well on. The GAI BB15 scores are better differentiators in this case since they emphasize, or proportionally represent, the difference in the gamut area enabled by the below BBL sources, especially in the saturated reds and blues.

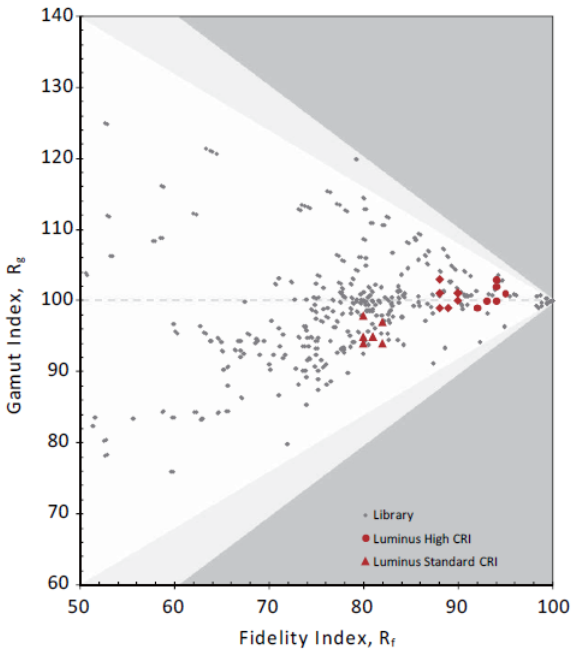

Figure 4: TM-30-15 improves on the common Ra (CRI) metric, but still has shortcomings.

LED sources with high CRI, such as the 97 CRI typical AccuWhite^{TM} from Luminus are centered in ANSI bins and achieve high TM-30-15 scores. LEDs with high scores like this have been setting the bar for color rendering, gamut, and fidelity in the most demanding applications. These are the go-to LEDs for specifiers who want to stick with the CRI metric and want to stay centered on the BBL.

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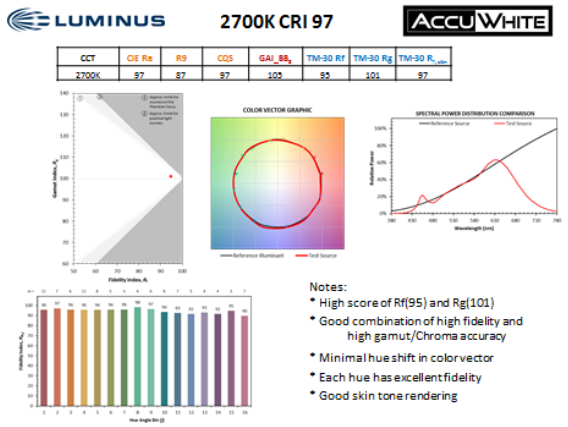

Figure 5: 2700 K 97 CRI (typical) "AccuWhite" is a premium benchmark LED source across various metrics.

Dr. Michael Royer, from the Pacific Northwest National Laboratory has recently hosted a webinar which raised some interesting points about the limitations of TM-30-15 and described possible upcoming improvements in the TM-30-18 standards that are under development. He also summarized the results of four recent experiments designed to gauge human preference of various light sources. In the four studies Royer identified, the subjects showed stronger preferences to the light sources which were rendering brighter, richer reds. He cited decades of research where men showed strong attraction to women when they wore red dresses and/or red lipstick. Red chroma was also a key attribute in the success of Kodak films, and red details in a photo or a live scene have a way of drawing the our attention and making the environment more alive and attractive.

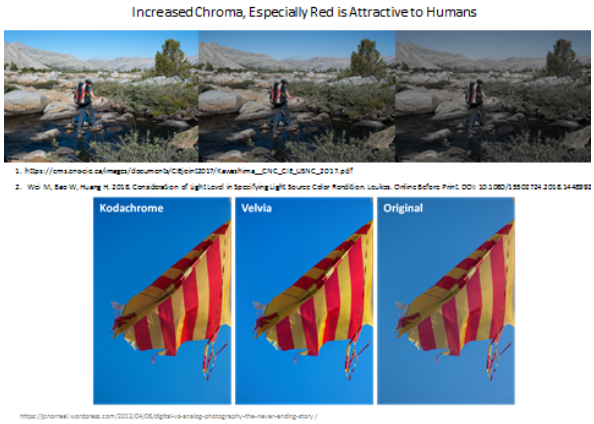

Figure 6: Rich reds on film was Kodak's advantage.

Some key takeaways from this webinar were the importance of red to humans and the conclusion that TM-30-15 needs further improvement. One great example of a problem with TM-30-15 is demonstrated by these two light sources characterized with the same TM-30-15 scores and the same CCT, but with completely opposite directions of red chroma shift. Without a doubt, the majority of us would strongly prefer the source with the richer red chroma, but if we specified our light sources with TM-30-15 scores, both sources would appear to be identical. Royer also gives a peek at the ways that TM-30-18 aims to improve on this type of scenario with the 16 hue angle bins, vector plots, and bar graphs. Even with improvements in TM-30, there is still a possibility that a spiked spectrum LED light source, like the old fluorescent bulbs, might score well but might not feel comfortable to humans. Most people who have been in a room lit with RGB LEDs, even those "perfectly balanced" to create white, will tell you that the light doesn't feel quite right. There's nothing like a smooth, broad spectrum light source to make us feel that our lighting is comfortable and natural. While it's hard to know exactly how the light will feel by just looking at the spectral distribution, we can do that in combination with other metrics to give us a full picture and ensure that we're getting the wavelengths that we want, and avoiding those which are undesirable for our particular application.

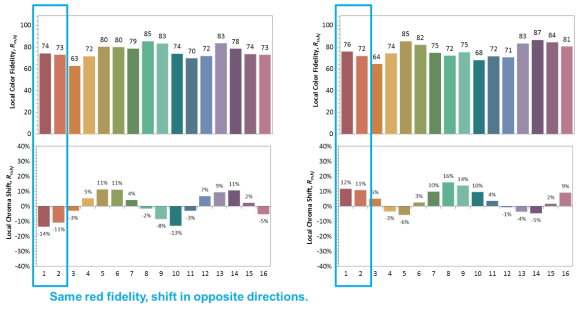

Figure 7: Two LED sources with the same TM-30-15. Vector plots reveal that these two LEDs are completely different.

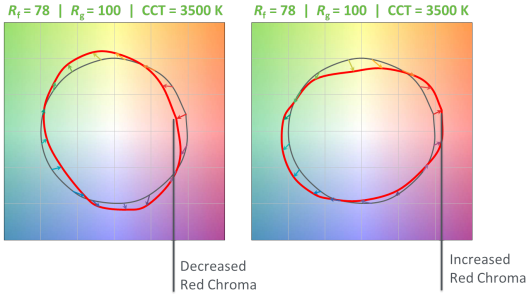

Figure 8: Two very different LED sources with the same TM-30-15. Hue angle bin bar graphs show red chroma scores in opposite directions.

One of the emerging trends in the past couple of

years is the popularity of “full-spectrum” light LED sources. There are several market needs driving this trend, ranging from a desire to simulate sunlight for a “feel good” effect, to a desire to replicate halogen, and human-centric applications, including those with or without strong blue and cyan content, to reduce or enhance melatonin levels within humans. In some cases, full spectrum LEDs are desired simply because they provide full, rich color rendering. Halogen bulbs have been popular for decades in some of the most demanding applications because of their full spectrum and attractive color rendering. High color rendering LEDs have been able to match the CCT of halogen and come close in CRI with typical ratings of 97 or 98, but most LED sources have a dip in the cyan range of the spectrum. Lighitng designers have long challenged LED manufacturers to fill the cyan gap and provide full spectrum, halogen-like illumination. Further, many focused on human centric lighting want to increase the melanopic ratios in LED sources to enhance alertness in people who are reliant on artificial lighting indoors during the day. Filling this cyan gap brings some challenges, but Luminus has done this quite effectively with a combination of the right LED chips and phosphors to create a smooth, full spectrum without any potentially hazardous violet or near UV wavelengths. This product, with the ambitious name of “PerfectWhite” has a full, broad spectrum, and it also renders colors beautifully, especially cyan, which is often overlooked in other light sources. The photos here show the cyan-enriched PerfectWhite COB compared to a halogen bulb and compared to a very popular standard LED with 3000 K and 90 CRI.

Figure 9: Standard 3000 K 90 CRI vs. Luminus cyan-enhanced “PerfectWhite”.

Figure 10: PerfectWhite full spectrum LED vs. Halogen.

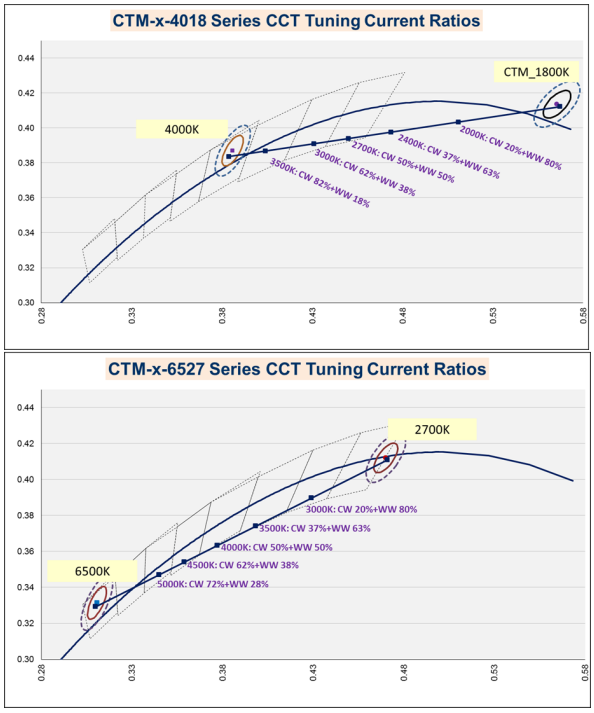

Figure 11: CCT Tunable light sources are a big trend in Human Centric Lighting.

Human Centric Lighting

Human centric lighting means many different things to many different people, but a trend which is growing rapidly in popularity, under ongoing study, and a hot topic of debate, centers around the amount of blue content in an LED spectrum. Eliminating blue is probably too extreme of a requirement, since we have been naturally under blue light throughout history, and most experts will agree that blue exposure during the day keeps our melatonin in check and our bodies in the proper circadian rhythm. While the PerfectWhite LED was really intended to fill the cyan gap, it has human-centric applications for daytime use indoors. Where the debate is running hot is at night, where some say we need a total absence of

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blue or at least a reduced level of blue, such as 5% or less of the spectral power. CCT tunable sources are gaining popularity, where the user can experience cooler, blue enriched light during the day, at 6500 K or 4000 K, and warmer, blue depleted light during the evening, such as 2700 K or even down to 1800 K, if you want to simulate a conventional bulb being dimmed down in your restaurant, hotel, or bedroom. Some specifiers are beginning to call out minimum melanopic ratios of light which are used in applications where they need people to be awake and alert. This could be in schools, factories, underground, or any other place where natural light is not available during daytime. This further drives the need for tunable lights, where the CCT can be controlled by balancing the current between two strings of warm and cool LEDs, such as the sources shown in this plot below.

Another hot trend is a dim-to-warm LED which uses a standard single channel dimmable driver and a standard dimming switch to dim the LED source. While the flux is being dimmed, the CCT is also changing from, for example, 3000 K at full power to as warm as 1800 K. Luminus warm-dimming technology even offers a choice of dimming curves, with a halogen style 3000 K that only changes to warm in the last 20% of the dimming curve or a linear style which changes CCT gradually with the change in current being applied.

As human centric products are emerging, plant centric or horticulture lighting systems are also bringing new ways of characterizing LEDs, and custom spectrums are in demand to optimize the needs of various crops at different stages of their life cycles. For example, lumens are irrelevant and are replaced with PPF (µmol/s) as the accepted metric for this market. Horticulture spectrums are usually focused in blue and deep reds, but they can vary widely to include UV, IR, or even traditional “warm white” LEDs. Systems focused on one crop might be static in their spectrums, but many are dynamic systems to fit many crops or livestock and to optimize the light to support the flowering stage, pest reduction, or other special purposes.

Conclusions

In conclusion, we are in a very exciting time when LED lighting can take full advantage of the flexibility of LED technology to create whatever we

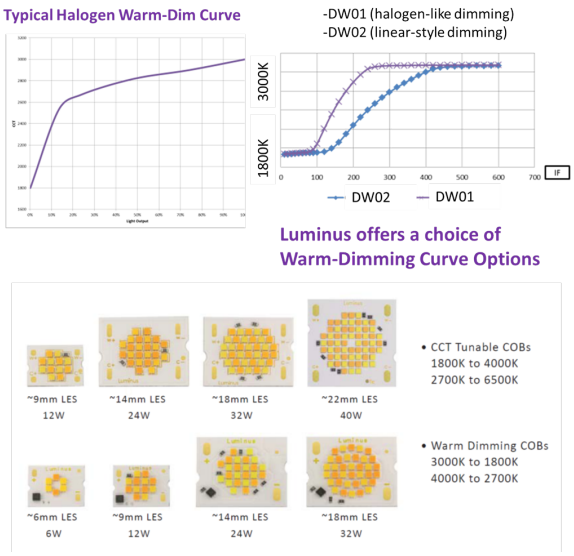

Figure 12: Dim-to-warm Dynamic COB modules create a warm, halogen or incandescent bulb-like glow when dimmed.

determine is a healthy spectrum in any application at any time of the day or night. I want to encourage you all to remember your red chroma,and keep your spectrums wide, smooth, and safe.

Acknowledgment

I’d like acknowledge Dr. James Zhai, a.k.a. “Dr. Color” from Luminus and Dr. Michael Royer of the Pacific Northwest National Laboratory for their material and inspiration spread throughout this paper.

Drivers, Connected Lighting & IoT

276 The Business Case for Connected Lighting and IoT Services Built on Top
by Thomas Moder, Tridonic

284 Benefits of an Information Centric Lighting Network
by Dr. Simon Slupik, Silvair

290 OpenAIS: Advantages of IoT Connected Lighting in Reality
by Dr. Stefan Verbrugh, Signify

300 Simulation Techniques During the Development of an LED Driver
by Antonio Cuadra Gimenez, ELT

308 Latest Development of Drivers | Control and Dimming
by Dr. Toke Meyer Andersen, Nordic Power Converters

316 Influence of Converter Topology on the System Interactions
by DI Markus Heckmann, OSRAM

326 DALI-2: Standardized, Interoperable Components and Smart Luminaires
by Dr. Scott Wade, DiiA

330 Connected Lighting Use Cases and End User Benefits: Fixture Based Control for Outdoor and Indoor Lights
by Dr. Peter Duine, Signify

334 Connected Emergency Lighting — Safety and Security in Controls and Emergency Lighting
by Jeremy Ludyjan, Fulham

338 Lighting System Based on Visible Light Communication
by Prof. Guido Piai (NOMINEE: LED professional Best Scientific Paper Award 2018), Interstate University of Applied Sciences NTB

346 Size Matters – Small Form Factors Drivers to Support Flicker-Free Airy and Artistic Luminary Design
by Keith Hopwood, Seoul Semiconductor

350 Requirements on High Performance LED Driver for Professional LED Lighting
by Ulrich vom Bauer, Infineon Technologies AG

The Business Case for Connected Lighting and IoT Services Built on Top

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Abstract

Connected Lighting as the basis of IoT systems are the words on everybody's lips at the moment. Industry players so are experimenting with and testing business cases for IoT applications that are built on the Connected Lighting infrastructure. Unlike other industries, such business examples, in many cases are not completely straightforward and require a substantial effort for prototyping and measurement, based on a thorough understanding of the specific customer's needs. The lecture takes a view on why this is the case and why it seems so tricky to build business cases here. It takes a look at the capital outlay for Connected Lighting solutions and their impact on operational expenditures. It further analyzes the position of multiple types of companies/players in the value chain and delivers a perspective on who is best positioned, and under what circumstances, to build a successful business.

Finally the lecture will cover successful deployments of IoT installations on the lighting infrastructure and elaborate on reasons why such installations have been successful and how they can be the foundation for a sustainable and successful business model.

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Introduction

This paper addresses the business opportunities and the business cases of Connected Lighting with respect to IoT services that can be built on top of the lighting infrastructure. It is not repeating the insights on business cases for LED lighting as a replacement of incandescent or fluorescent lighting, nor does it focus on the business case of dimmable lighting. These topics have been addressed on many occasions already and, to be fair, we'll just summarize the industry's general consensus that the introduction of LED lighting can reduce energy consumption by approximately 60% to 70% while the introduction of dimmable LED lighting (or in other words "lighting management solutions") compared to non-dimmable LED lighting gives us a further 20% to 30% energy reduction for the lighting system.

Neither does this paper cover the business case of "wireless lighting" that obviously provides a brilliant business case in refurbishment situations as it reduces the need to pull in wires in order to connect the luminaires to a central lighting management system that provides comfort and cost savings.

This paper though focusses on the investment (is it an investment) in a lighting infrastructure (including hardware, software, installation, commissioning, operation, maintenance) that comes with connectivity and interfaces which enable a new level of IoT services, comfort and cost savings for a range of stakeholders. The recent acquisition of Enlighted Inc. by SIEMENS has shown that big industry players are nowadays realising the value of "Connected Lighting" — otherwise why invest in it. [1]

Even though the consumer electronics industry works differently to the lighting industry and is a B2C business rather than a B2B business, we can anticipate how things can develop. For that, we draw a comparison between the development of mobile phones and luminaires. What if luminaires (or mobile phones in comparison) suddenly widened their application from lighting (corresponding to voice calls) to data driven services (corresponding to apps)? Such services could be introduced by higher bandwidth IP connectivity and a wide range of sensors as part of the lighting infrastructure. Needless to say, nobody could actually anticipate the market dynamics of the apps ecosystem once iOS and Android interfaces became available to a huge developer community. Even Steve Jobs himself was initially against opening the iPhone for 3rd party apps. We will use the example of mobile phones here and there throughout this paper.

Business Case Criteria - Hard and Soft Facts

The lighting industry and lighting industry players frequently watch each other to watch the decision they make as well as trying to anticipate their competitor's next moves. New business opportunities frequently arise from adjacent areas and occasionally true disruption enters the stage from an area the well-established companies did not expect. To illustrate some examples of market developments that hugely transformed the business landscape let's remember that:

- APPLE vaporized NOKIA's relevance in the smartphone arena by creating devices and services around data rather than voice.
- CISCO was one of the first that believed in voice transmission over IP infrastructure and eliminated the need for separate cablings and installations for telephony systems.

The results of looking at these examples leads us to ask what lighting companies would add to the lighting installations to prevent competitors coming in and using their products to illuminate the building.

In general, when we talk about business cases, most of us immediately think about complex excel spreadsheets that perform extensive calculations based on investments in CAPEX and OPEX versus revenues (or cost savings) which they will realise over time, merge in some interest rates that have been agreed on with financial controllers and spit out some numbers on contribution margin, gross margin or EBIT. For the purpose of this paper we will determine these facts and business cases as HARD. HARD facts can be measured in hard currencies — Euros, Dollars, . . .

But there are SOFT facts that might translate into successful business cases. While the investments in these cases are very well quantifiable, the revenue, profit and savings are actually not or — at the very least — a formula cannot easily be created. That is, because these cases do not aim at a monetarily measurable objective but rather at

qualitative objectives. How would we measure employee wellbeing or productivity easily in Euros or Dollars? Or how would we translate air quality in urban environments into a monetary number easily?

It remains certain that these investments are beneficial or "profitable" in a different sense, and they might even be translatable into numbers, but not always into Euros and Dollars. While better air quality in cities might result in a healthier population that lives longer, more people might be attracted to the city conducting business and paying taxes there. Increased public safety might also lead to more comfortable citizens whilst noticeably reducing the number of injuries, crimes or even deaths. All these examples are measurable in numbers but hard to translate to the Euros or Dollars that I could easily compare against the conducted investments.

Companies, communities or countries apply HARD and SOFT business cases in a mix which is different from case to case. They are driven by economic considerations but are increasingly fueled by a social responsibility which companies must adopt for their employees, or communities embrace for their citizens. Why otherwise would companies invest into free coffee and fresh fruit for their employees, create nicer work places by putting sofas and kitchen corners into the office floor? Why otherwise would cities want to become smart by investing in infrastructure that can help people find free parking spaces, in video surveillance that increases public safety or — in some geographical regions — infrastructure that detects the sound of a "gunshot" and sends police authorities there immediately [2].

The Cost of Connected IP Based Lighting Systems

The OPEX COST of DATA

When we talk about IoT services that are built on top of the lighting infrastructure, they all have one thing in common — they all rely on data which the connected lighting infrastructure delivers and the data type itself, in addition to the quality, frequency and granularity of such data. It makes a big difference whether I have ONE occupancy sensor in the middle of a room or an occupancy sensor as part of EVERY luminaire. While some information might be good enough to indicate that a meeting room is busy, the same level of information is not good enough to judge whether the range of meeting rooms in a company is used economically or whether it is used by employees primarily for private phone calls.

With the consumer economy of "free cloud storage" it is important to clean up the myth that the cloud comes for free. Connected IoT devices are constantly creating a mass of data that MUST be stored and managed by a powerful platform. Storing millions of data points with an update frequency of minutes or even seconds creates a data cloud that MUST NOT be underestimated in terms of platform performance and cost. While platform performance might be scalable easily by using 3rd party cloud platforms like AWS, MS Azure or others, the cost of this upscaling has the potential to easily ruin the business case for many applications. Data handling should be considered carefully — holding the presence value of a specific sensor for 6 years with a frequency of 1 minute might not make real sense, while it might be useful to have that data available for some months for analysis. IoT applications should handle data storage cleverly and with care.

Although the customer value of the data is not depending on the cost to manage such data, the balance between the customer value and cost must be carefully monitored to yield a future-proof business case. The cost of maintaining and granting API access to such time series data grows with the amount of connected nodes (luminaires, sensors, . . .), the size of individual data points and the frequency to collect this data (once per second, once per minute, once per hour, . . .). It also grows with the frequency to access these data via the API. Storage and computational efforts for this are usually necessary and far away from costing fractions of cents, as the economy of free cloud storage and low-cost-high-bandwidth internet connections might make us believe.

Below (see Figure 1) is a screenshot (see taken from `https://www.carriots.com/pricing` on 11 June; so numbers might have changed in the meantime. However it paints a good picture of the market costs and prices for the collection of and access to a large database of sensor data. It is important to note that these prices come without any specific application behind the data that might in the end capture the real end customer value. Other examples are available on `https://cloud.google.com/iot/pricing`, `https://azure.microsoft.com/de-`

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de/pricing/details/iot-hub/ or https://azure.microsoft.com/en-us/pricing/details/time-series-insights/. By no means can these costs be neglected when calculating the business cases for lighting based IoT solutions — the costs per connected device can range easily from €0,50 to €25,- per year.

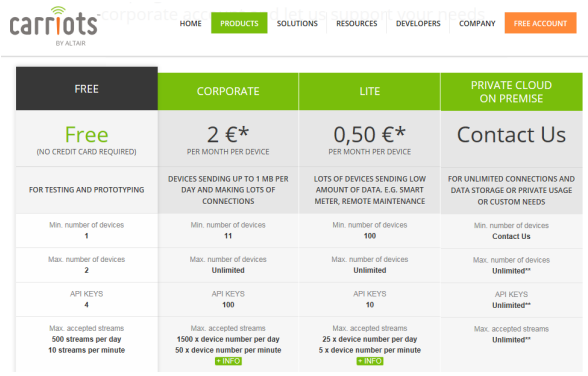

Figure 1: Examples of the costs for databases.

This cost imposes an enormous challenge on the value of the applications that are built on top of the data. That value at times is not easy to deduct — we will look at various applications in chapter 4.

The CAPEX cost for a Connected Lighting Infrastructure

To be precise, we would like to define what we consider to be a Connected Lighting infrastructure which we consider to be the base for IoT applications. The key point we want to make here is that luminaires (or groups of luminaires), sensors (or groups of sensors) are connected by a means of communication technology that is suitable to transmit all kinds of data — various data types, sensor types — and that is not limited to lighting related data.

Today's DALI technology is designed around lighting from simple applications to Human Centric Lighting and Emergency Lighting, but as such is not open to transmit information that has not been considered at the time of the DALI protocol specification. Wireless technologies like Zigbee and Bluetooth have widened the scope of data that could be exchanged between participants but ultimate flexibility can be given only through a system that utilizes the IP protocol stack that is open to host the exchange of simple messages, in addition to complex and continuous data streams. TRIDONIC has adopted that thought by basing the communication of its net4more platform fully on IP — embracing IPv6 on the wireless communication side and PoE (Power over Ethernet) on the wired side.

Such a new communication standard seems to come with additional expense when compared to a traditional DALI based installation but that is not necessarily the case. The cost of expensive DALI wiring and DALI based commissioning will be negated by using wireless communication modules or standard IT equipment that is setup easily and prevents wiring failures at the time of installation.

When we return for a second to the development of the Smartphone world, we could see 2G evolving to 2.5G, further developing to 3G, 4G and finally LTE. Each and all of those transitions happened in a way that the succeeding generation of chipsets was more expensive initially but, through mass market adoption, quickly becoming in-line with the preceding chipsets. For the lighting world, this means that IP based lighting systems will be on the level of DALI based lighting systems very soon, but it also means that IP based lighting infrastructure (with the IoT services it enables) and DALI based lighting infrastructure (without a range of services) will co-exist for some time — as 3G and LTE did in the world of mobile phones.

TRIDONIC proposes that IP based lighting infrastructures CAN be available for the same CAPEX as traditional DALI based systems today and already are. Combined presence sensors with wireless connectivity are available today at prices that are not far away from DALI based sensors. While the DALI based sensors inside and outside luminaires require special effort and attention when wiring them together, this effort fades away in the case of a wireless solution. Wireless though is not the answer for any application, as constructive limitations or security concerns can be problematic. PoE systems might be useful here. Because while the PoE infrastructure might still be expensive today, its price will heavily drop in the future, reducing the "price per connected node" to a level comparable to DALI.

Below picture (see Figure 2) shows how TRIDONIC anticipates prices for IP connected nodes (LED driver + communication module + sensor) will develop over the next couple of years.

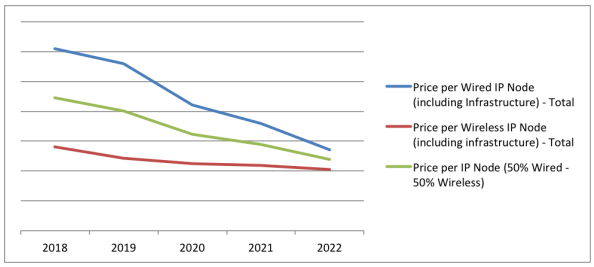

Figure 2: Price development of Connected Lighting Nodes (Driver, Sensor, IP Communication including infrastructure part per node).

The Value of Connected Lighting — There's No OSFA (One Size Fits All)

However, the question on the value of the collected data is a difficult one and there is no definitive answer. If we turn back for a second to the comparison with consumer electronics, we could clearly conclude that the value of data is determined by the number of apps that are making use of such data. If we take an accelerometer sensor, for example, as part of a smartphone, the data it delivers enables a lot of highly attractive games. We can immediately conclude that the amount of applications making use of the data heavily determines its value.

But even within the area of mobile gaming, a simple game where you only tilt the phone to balance a ball into a whole will not cost you as much money as a full suite of racing games where you put yourself into a Formula 1 driver's seat to immerse yourself in the Monaco Formula 1 course. So, we can conclude that the value of the data is also determined by the value of the application that is built on top of the data.

If we do translate the above findings into the lighting environment, we can conclude at least 2 things: To maximize the value of the data that the lighting platform provides, the lighting platform must provide an open API to access this data easily. Such an API should be both locally available in the building to retrieve the latest status of the system with lowest delay (corresponds to the accelerometer value used in gaming) and as an interface that provides the complete time series data for analysis creating insights (corresponds to the accelerometer value used in a step counting application). TRIDONIC's net4more platform is a good example for using exactly such an approach (see Figure 3, Figure 4, Figure 5). Sensor data and luminaire status can be accessed both locally — for integration into a building management solution — or via cloud interface, to enable time series data analysis to optimize operational efficiency like room usage, energy bill or employee satisfaction.

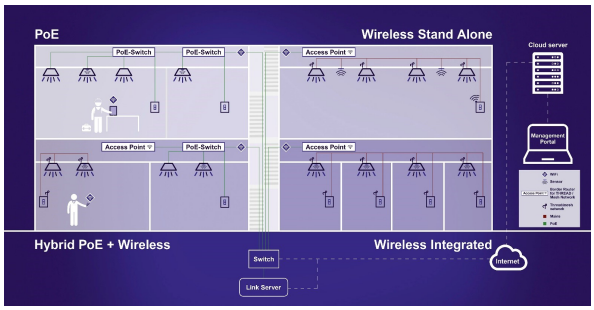

Figure 3: Open net4more APIs.

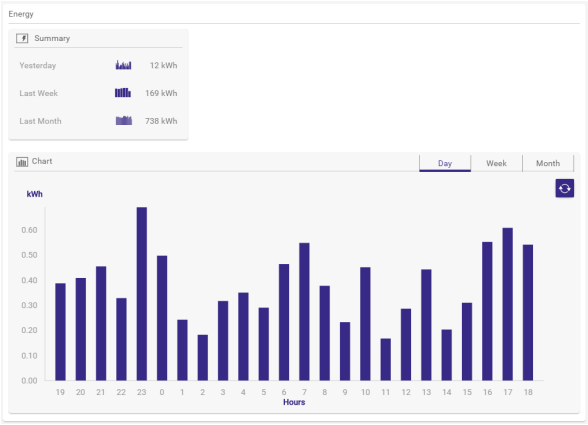

Figure 4: Example for application built on the net4more API.

Figure 5: Example for application built on the net4more API.

Example for Office Applications (1)

Business cases for office applications are mainly built around operational savings and productivity increases — we could also say an increase in

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employee comfort. While the first group — operational savings — are easy to measure and can be translated into Euros easily, the second group is more difficult to assess. We will try to outline both.

According to chapter 3, the CAPEX for the installation of an IP based lighting system that hosts luminaires including traditional daylight/presence sensing is already on an equal level with a DALI based lighting installation. To reduce operational spending, data and control from such lighting management systems can be handed over to overarching building management systems via BacNET, KNX or IP interfaces. Other domains like climate control and shading systems can be orchestrated in a way that makes additional operational savings a reality.

Now, of course, the collected presence information from the deployed sensors can give us much more in terms of operational savings by conducting proper analysis of the time series data that is available on the cloud. Let's get back to the previous example. If we were constantly transmitting the presence information of 1000 sensor nodes into the cloud database, as we have seen in the previous chapter that can easily generate costs of €5.000 per year. A services company that focusses on the statistic analytics of that data, that comes with proven application experience on what can be considered as an over or underutilized space, will not do that for free. They will charge for the analytics potentially on a square meter base — say 2€per sqm. Assuming that a luminaire serves a space of 5 sqm, there is a space of 5.000 sqm to analyze and consequently a cost of €10.000 to cover.

Altogether the end customer — in this case the tenant — would be charged €15.000 per year to learn about the utilisation of the rented property. For our example above (5.000 sqm with a monthly sqm rent of €10 translating to a yearly rent of €120/sqm), this would mean that the customer would need to realize efficiencies of 15.000/120 = 125 sqm, that equal 2,5% of the rented office space. A value that is quite realistic but that would need to be sustained over the next years.

Example for Office Applications (2)

While the example above is guiding us with hard facts and measurable Euro expenditure, the second example represents a situation in between a HARD and a SOFT business case. It is undoubted that the working environment has an impact on employee satisfaction and employee productivity. Researchers in the US have conducted studies which show that the air quality can yield a productivity improvement per employee as big as $ 6.500 annually [3]. Surprisingly, such air quality analysis might not even need sophisticated time series data analysis but can be achieved by simply connecting the IP based lighting system by means of a BacNET Gateway, KNX Gateway or, even simpler, through pure Software IP integration with an overarching BMS Management platform. Consequently, the additional cost of such a solution compared to a standalone DALI based lighting system would be the addition of CAPEX into a suitable set of sensors in a sufficient density. Assuming that air quality sensors would go along with every luminaire and, in a modern office building, 2 luminaires would correspond to one employee and such productivity improvement "per employee" could seemingly be achieved by the deployment of 2 air quality sensing nodes, plus an integration of the lighting installation (via physical gateway or pure software) with the intelligence of climate regulation based on the set of sensing data that the lighting system delivers. With the assumption that sensors for commercial grade air quality measurement are available for below the 100 Euro range, one can easily imagine that there is positive movement between 2× €100 for the sensors and the integration with the BMS and the yearly $ 6.500 productivity improvement.

A personal side note is allowed — the authors are rather careful in translating a single means of investment into a directly measurable "productivity improvement" for office workers. In the end, productivity is always a result of many different influences including the comfort and health of the working environment. Such positive health can be achieved by a sum of "free fruits at the workplace", "sofa corners", "height adjustable desks", "excellent cappuccino" and, of course, Connected Lighting. It remains unchallenged that a sophisticated lighting system — be it by circadian rhythm implementation or by taking care of a healthy indoor climate — contributes to wellbeing.

Example for Retail Applications

Many of today's wireless lighting control systems are heavily betting on Bluetooth as wireless communication standards. Those Bluetooth Low Energy solutions are coming inherently with Beaconing functionality that allow location based services. So what is closer to just activating that functionality for exactly that purpose? The hardware comes with no additional cost. That's exactly what Zumtobel Group Services did with French Retail giant E.Leclerc Langon. The location information was connected via a customer smartphone app to a localisation platform that gave Leclerc valuable insights into their customers' shopping behaviour. These insights have been shared with Leclerc's customer loyalty program.

Leclerc motivated a large group of their loyal customers to install an app that, amongst other things, informed their customers about location based offers in their retail shops, i.e., when being close to a special offer that might be interesting for those customers, they received a push notification.

The results showed that this kind of "push marketing" increased the revenue per customer by, on average, 34% to 42% (depending on the test group). Those are HARD numbers, where it is easy for the retailer to assertain from the purchases of customers that have joined the customer loyalty programs and the product profits, what level of investment would lead to a profitable business case. As Connected Lighting systems might be installed anyway, there might not be an add-on cost for the hardware, but the major investment would be the programming of the application (on the smartphone and on the cloud side) and the integration of the application with Leclerc's customer loyalty program.

Interviews with the test customers also showed that they were highly satisfied with the new kind of shopping experience and customers admitted that, as the objectively measured data suggests, they would be increasing both the value of their shopping basket and their frequency of visits to the store. A clear win-win situation for both Leclerc and its customers [4].

Conclusions

Business cases of IoT solutions based on a Connected Lighting infrastructure are a complex area and the profitability of such solutions cannot be judged without looking into each specific case and understanding the end customer's challenge or pain point. While the cost of an IoT solution based on a Connected Lighting infrastructure is well understood, there are a lot of ideas out there in the market that will still need to prove a HARD and quantifiable business case. While some of these ideas might remain questionable for some time, others might yield to an obvious HARD business case at first glance (example Leclerc). Beyond those cases, where investors will calculate HARD business cases with close scrutiny, we will see Connected Lighting systems evolve to use cases beyond lighting as companies and communities will be increasingly committed to their social responsibilities which cannot be delegated elsewhere.

The key for lighting based IoT systems is the openness of the platform that provides an incubator for a lot of smart and innovative companies which are sitting close to end customers (tenants, facility managers, investors) — actually closer than lighting companies are — and that will unleash the potential of the collected data towards the end customer. TRIDONIC believes in that openness of platforms and has therefore designed its net4more system with that in mind.

As we return to the comparison with the Smartphone revolution one last time, we need to confess that we are currently at a comparable stage to when Apple and Google released their first set of APIs for app developers. Similarly, the lighting industry is ready for an exciting future!

References

[1] https://www.siemens.com/press/en/pressrelease/?2press=/en/pressrelease/2018/corporate/pr2018050194coen.htm

[2] https://spectrum.ieee.org/computing/it/san-diego-installs-smart-streetlights-to-monitor-the-metropolis

[3] https://www.memoori.com/harvard-study-supports-growing-body-research-linking-air-quality-productivity/

[4] https://www.zgservices.com/assets/press-release/9_ZGS_2103_Project_ELeclercLangon_DE.zip

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Benefits of an Information Centric Lighting Network

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Abstract

The last decade proved how challenging the lighting environment is for wireless communication technologies. Connected lighting seems to be stuck somewhere between the “innovators” and “early adopters” stages of the technology adoption curve. The fact that even the most proven wireless solutions were unable to provide wire-like reliability, simplicity and commercial-grade scalability shows one thing. A radical change is needed in how we approach the fundamentals of connected lighting.

Information-centric networking (ICN) is a revolutionary concept developed to address the challenges relating to the exponential growth of data traffic across the Internet. But its major paradigms can be applied to other networking technologies. Moving away from a host-centric architecture, ICN doesn’t care about senders, recipients, addresses. Instead, named information is its focal point, making data independent from location, application and storage.

The ICN concept can also be applied to wireless lighting control technologies. This produces indisputable benefits, including streamlined data exchange process and drastically improved scalability. I will explain what ICN means for connected lighting and how it can be implemented in the lighting environment. I will also describe how the Bluetooth mesh specification embraces the information-centric communication model to solve the three pain points of today’s wireless lighting control systems: simplicity, scalability and reliability.

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Introduction

Over the last couple of years, we have seen a number of wireless solutions emerge on the market, promising to revolutionize a decades-long lighting control paradigm. Indeed, the concept of connected lighting has an enormous potential, from helping us address global sustainability needs to making our working environments healthier and more comfortable. In professional applications, wireless lighting controls promise energy savings, design flexibility, nondisruptive retrofitting and multiple value-added services on top of it all. Considering how much value connected lighting could generate on a global scale, we could expect that things would progress fairly quick. But it turns out that the road from concept to implementation is surprisingly long. It's 2018 and wireless controls still seem to be a thing of the future. There are plenty of promises but very few use cases. Multiple products but no agreed standards. And more importantly — still no answers to a number of major challenges.

What is holding us back?

A number of factors contribute to the state of connected lighting a.d. 2018. Some of them are known pretty well. Technological fragmentation and the lack of interoperability have been discussed multiple times, also during the previous editions of this event. Is there any progress in this regard? It's disappointing, to say the least. We should not expect miracles, though. Both these issues are not easy to deal with. This is not something that can be addressed by a single company or even a group of companies. Industry associations focused on connected lighting are important, but their growing number can paradoxically make it even harder to address such problems. So how can you reduce fragmentation and increase interoperability in a fledgling yet promising sector? What can be done to address such market-wide, business-related challenges that keep preventing widespread adoption of connected lighting in professional applications? Well in the end it all goes down to technological issues. Both market fragmentation and the lack of interoperability result from the fact that throughout all these years, we didn't witness a wireless control solution that would truly stand out from the rest. There has been no champion; no wireless king that would be able to provide what we expect from smart lighting in the first place — flawless performance. Wire-like reliability. With wired systems, the industry has learned how to tackle the most difficult, sophisticated installations. With wireless systems, we've barely touched the surface. Throughout the short history of connected lighting, no matter what solution you had chosen, you would eventually hit a wall. That wall would usually be the scale. Or industry-grade reliability. How could that be if there is so much value awaiting in the smart lighting segment? Why couldn't we make wireless systems just do their job in the golden age of technology and computer science?

Lessons learned

Perhaps 2018 is the high time to admit that we did it wrong. That certain ideas were doomed to fail. Over and over again, we've seen the connected lighting concept being implemented using the approach known from classic IT networks. This direction seemed natural, but connected lighting turned out to be a huge challenge. It requires low-power, low-bandwidth wireless technologies to deliver robust performance and fully synchronous operation in networks that often scale up to thousands of nodes. With all the conflicting requirements of the connected lighting environment, communication technologies based on traditional IT paradigms were simply unable to deliver wire-like reliability and responsiveness in commercial-scale installations. To learn why — and to find out what can be done about it — we'll have to take a look at a broader picture. Many lessons can be learned from the biggest computer network known to humankind, the Internet.

Networking technologies we commonly use today are based on a host-centric paradigm. Perpetual connectivity, the so-called end-to-end principle and the client-server model for data exchange have become a design framework in computer networking. This is how the entire Internet infrastructure is organized. But the concept of this architecture was designed decades ago, and a lot has changed since then. With the rapid advancements in such fields as mobile technologies, video streaming or cloud computing, the traffic volume is increasing at a rate higher than ever before. And today's Internet is an enormous clutter of never-ending communication loops, redirections, repetitions and, ultimately, inefficiencies. Think about a viral video stored on a server somewhere in the U.S. Each time someone wants to view that video, data

needs to be pushed all the way to his or her computing device.

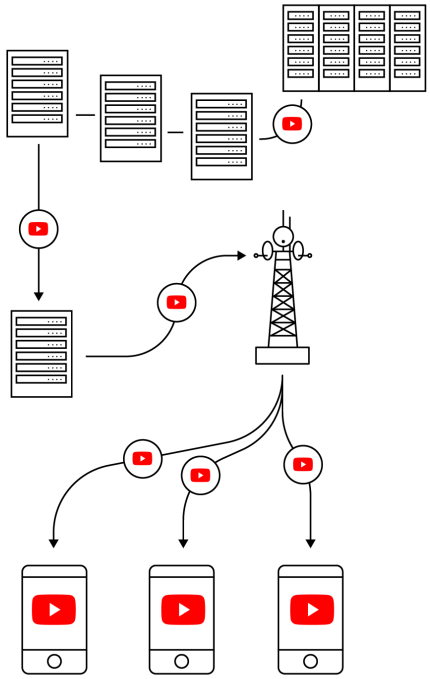

Figure 1: A long journey between the content source and user's device in the host-centric infrastructure of today's Internet.

This is a very physical process and as part of it, data often needs to travel literally halfway around the world. We've learned how to effectively transfer data over huge distances, but the rapidly growing scale of data-heavy online requests is becoming a problem. To address this problem, IT scientists have come up with a concept that solves multiple issues relating not only to the Internet, but also to other modern networking technologies. Connected lighting happens to be one of them.

Enter information-centric networking

Information-centric networking (ICN) is a concept developed under the Internet Research Task Force (IRTF) [1], a body focused on long-term research related to the evolution of the Internet. It is an approach to evolve the Internet infrastructure and support its dynamic growth by introducing uniquely named data as a core Internet principle. Moving away from a host-centric paradigm, ICN doesn't care about senders, recipients, addresses. Instead, named information is its focal point, making data independent from location, application and storage [2].

The key paradigms underlying the ICN concept include decentralized architecture, multicast communications and publish-subscribe data exchange model. Designed to address the multitude of redirections and repetitions haunting the Internet today, ICN effectively solves the problem of heavy data traffic being transferred over the same route over and over again. Instead of requesting data transfer from a host server located somewhere in the world, users' devices can access it from the nearest location where this data can be found. So if you're watching that Superbowl game on your smartphone, your neighbor who happens to be doing exactly the same thing could give you a helping hand, while at the same time reducing redundant Internet traffic. The ICN concept effectively removes data bottlenecks across the network and eliminates points of failure by enabling information to be independent from location. This significantly increases the efficiency of the data exchange process, while making the network more scalable, reliable and efficient.

Of course, the Internet is an enormous and complicated space, so it will take years before we witness the ICN architecture fully deployed there. The concept is still under development and we're yet to see what the transition towards the information-centric model will exactly look like. But its core paradigms can be applied to smaller-scale environments today. How do they apply to wireless lighting control systems?

Information-centric lighting networks

The host-centric paradigm is the approach that has been used in all connected lighting solutions so far. And it didn't prove efficient enough. With bottlenecks typical for gateway-dependant networks, low-power wireless technologies with limited throughput faced similar barriers that the Internet is about to face as it continues its exponential growth — scale of the network and reliability of data delivery. And similarly as in the case of the Internet, these challenges can be addressed by putting information at the center.

Figure 2 compares how information is distributed

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in a typical wireless lighting control network and in a wireless lighting control network utilizing the ICN concept.

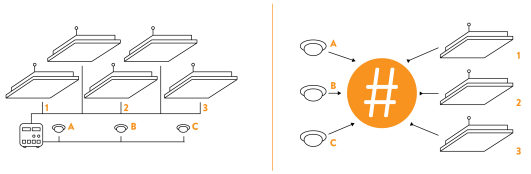

Figure 2: A host-centric lighting control system vs an information-centric lighting control system — logic and architecture.

In a host-centric smart lighting network shown on the left, all data is sent to a controller and back. The controller not only becomes a single point of failure (once it fails, the entire network goes down), but also generates bottlenecks that affect the packet delivery rate and, ultimately, the throughput of the network. Just like in today's Internet, data keeps traveling between individual nodes over and over again. Addresses of individual devices are necessary to deliver any piece of information to a desired recipient, so sensors keep pushing information to the controller and the controller then pushes the commands back to each of the associated fixtures, multiplying the traffic volume. In large-scale installations, this communication becomes quite a mess. The efficiency of such network is very low, which is a serious issue for lighting applications where instant responsiveness is taken for granted. Heavy traffic is not what low-power wireless technologies are built to deal with, so they struggle to reliably and efficiently deliver lighting control messages under such circumstances. In a host-centric network, communication between individual nodes is similar to email communication we all use. To say something to a specific person, you need to type his or her email address, compose a message and click send. There is nothing wrong about emails, but sending an "off" command to a ceiling with 50 fixtures is like sending 50 separate emails. Not the most efficient way of communication. Plus, you need to precisely know the 50 addresses. And what if some of them have changed?

The way an information-centric network works resembles, in contrast, Twitter communication — hence the hashtag on the right part of figure 2. Addresses are assigned to information, not to specific devices. Luminaires subscribe to these addresses so that they can respond to relevant messages. Other devices (sensors, switches) publish to these addresses, distributing lighting control commands among all interested parties at the same time. So if we get back to our example with a 50-fixture ceiling, in ICN you don't need to send 50 separate emails. You just publish your content to a relevant hashtag. And all your buddies who have subscribed to that hashtag will immediately see it. So instead of sending 50 "off" commands to all the luminaires in the room, you basically need to publish only one message — all luminaires that are supposed to respond will do it. This is the essence of information-centric networking. Let's take a look at more examples.

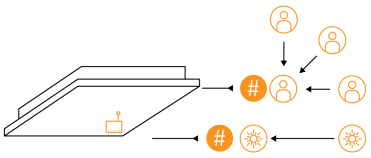

Figure 3: Sensors publish data to #OccupancyStatus and #AmbientLightLevel addresses, while luminaires subscribe to these addresses and respond to obtained information.

What exactly this "named information" is in the case of lighting control networks? As shown in figure 3, this could be the occupancy status of a particular room. Since ICN assigns addresses to information, this occupancy status is going to have its unique address. The ambient light level in that room will have an address, too. And it doesn't matter how many sensors contribute to that. Relevant sensors will publish information to these addresses, while luminaires that are subscribed to them will be able to respond to occupancy or ambient light level data from sensors. In addition to streamlining the communication process, such an approach solves such issues as device replacement. If a luminaire requires replacement, the new one only needs to be re-subscribed the same way as the previous one. There is no need to change anything in the configuration of sensors interacting with the replaced luminaire.

But as shown in the figure 4, the address can be assigned also to, e.g., the health status of luminaires, so that they can publish their operational data there. This way, administrators can easily access all such data in one place, gaining a comprehensive insight into the entire network.

In addition to being more reliable and scalable, a

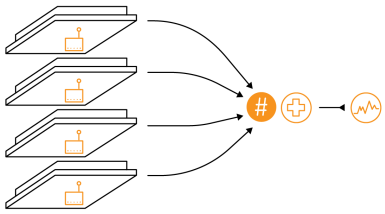

Figure 4: Luminaires publishing their operational data to #HealthStatus address.

wireless lighting control system utilizing the publish-subscribe paradigm is also easier to handle. It consists of simple, uncluttered relationships between groups of devices, enabling easier management, maintenance and — if the lighting needs change in a given space — also reconfiguration. To be fully in line with the ICN concept, such network also needs to be decentralized. This means no gateway devices and no control boxes that could constitute single points of failure. Therefore, the logic configuration needs to be dispersed and not condensed within a single device.

All this is quite an impressive set of requirements. To fully realize the ICN approach, a wireless technology needs to move away from networking paradigms of the past century. The information-centric approach is extremely powerful, but it does constitute a challenge in itself. It is just an entirely new quality, full of revolutionary concepts. How to implement them in the lighting environment? Thanks to the recent developments in the wireless industry, this could be easier than one might suspect.

Bluetooth mesh: ICN for lighting

The Bluetooth mesh standard adopted last year is a wireless technology based on the ICN principles. The previous versions of Bluetooth gained global recognition as reliable solutions for the applications they were intended for. But Bluetooth mesh is very different. It implements all of the major paradigms of information-centric networking in order to enable simplicity, scalability and reliability — the three pain points of wireless lighting control systems. First qualified products are now available, with multiple others on their way to the market. What is particularly important, the Mesh Model Specification — one of the three specifications defining the Bluetooth mesh standard — covers all aspects of lighting control and sensing, providing a complete foundation for building robust and scalable lighting control systems.

Bluetooth mesh achieves unprecedented scalability by combining the above mentioned ICN paradigms with unique mechanisms increasing the efficiency of radio communication. First of all, it introduces a fully decentralized architecture with no bottlenecks or single points of failure. Being natively supported by virtually all personal computing devices, it enables smartphones and tablets to communicate directly with network nodes, with no gateway in-between. It also doesn't require central controllers, since it puts controllers into each luminaire. With such a dispersed logic configuration and multi-path packet delivery, Bluetooth mesh networks are exceptionally resilient. Bluetooth mesh networking also supports multicast communication and implements the Twitter-like publish/subscribe paradigm described above, putting information at the very center and effectively streamlining communication across the network.

These innovative communication concepts, coupled with efficient wireless transfer capabilities of the Bluetooth Low Energy radio (ultra-short messages, high spectral efficiency and high data transfer rate) is what makes Bluetooth mesh networks so robust and scalable. In addition to its impressive scalability, Bluetooth mesh provides additional measures that help confine heavy network traffic in extremely dense, large-scale commercial implementations. One of them is the concept of subnets. With a single mesh network capable of accommodating more than 4,000 subnets, Bluetooth mesh should be able to cover any building automation system we could possibly imagine today. Furthermore, Bluetooth mesh can use three different frequencies, which means that available raw radio resources are significantly larger than in the case of protocols operating on a single frequency.

Bluetooth mesh also has solutions for the typical challenges relating to the commissioning of connected lighting systems. Since the Bluetooth radio can be found in any smartphone/tablet on the market, such devices can be used as network provisioners as long as a relevant app has been installed that reliably and securely supports all the required processes. What's important, from the

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perspective of both network formation and other stages of commissioning, no gateway is needed to connect with individual nodes and set up the entire mesh network. Bluetooth is the only radio technology that allows for forming the network without touching the building's core IT infrastructure. It doesn't require gateways or Internet connection, so there is no need to obtain any formal agreements from the IT department — a process that can literally take months in the case of more sensitive buildings, such as banks or hospitals. When it comes to device identification and mapping, communication with no gateway in-between also generates significant advantages. Since a smartphone can connect with any other node directly, Bluetooth's RSSI capability (Received Signal Strength Indication) effectively solves the problem of device identification. Simply put, when your smartphone is communicating with a particular network node, it can tell how far this node is. In practice, a smartphone app can use the RSSI filter to narrow down the list of displayed luminaires and sensors to those that are located in your immediate vicinity.

Last but not least, Bluetooth mesh addresses the problem of interoperability mentioned in one of the first paragraphs. With its fully defined application layer and rigid qualification procedure, this new wireless standard opens up a global lighting control ecosystem where products from different vendors can work with each other out of the box. Driven by more than 33,000 members, the Bluetooth Special Interest Group has 20 years of experience in developing globally successful and interoperable wireless standards. Its latest invention, Bluetooth mesh networking, introduces so many revolutionary concepts to wireless lighting control that its adoption truly marks the beginning of a new era for connected lighting. The era of information-centric lighting networks that finally can match wired systems in terms of reliability and scalability.

References

[1] Official website of the Internet Research Task Force (`http://irtf.org/`)

[2] Official website of the Information-Centric Networking Research Group (`http://irtf.org/icnrg`)

OpenAIS: Advantages of IoT Connected Lighting in Reality

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Abstract

OpenAIS (`www.openais.eu`) was a project sponsored by the EU in the Horizon2020 program, running from 2015–2018, in which seven leading European companies and two academic institutes cooperated on the creation of an IoT-based professional lighting system. In 2014 the goals of this project were defined as: to create an open architecture (standard) for lighting control systems in the 2020's, allowing multi-vendor installations, based on (by then emerging) IoT-standards and ecosystems and to validate this approach by a large-scale pilot in an actual office environment. See [1].

The OpenAIS architecture for Lighting Control Systems targeted at professional applications and created an architecture building upon the IoT-infrastructure that was released last year [2] [3]. Demonstrating the promises of interoperability and third-party mix and match was another important objective of the project. In early 2018 this was fulfilled by disseminating the results of a large-scale pilot (more than 400 luminaires) in an operational office, the historic White Lady building in Eindhoven. The set-up of the project and the results and learnings from the pilot have been reported back through a symposium [4] and in earlier articles on the subject [1]. In the current article we will report on the experiences with the assumed benefits of IoT-connected lighting. For this we will look at the advantages of such an IoT-based lighting system from multiple angles: The building value, the ease of installation and the emergence of a building wide ecosystem, reducing Research and Development cost and accelerating value growth.

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Introduction

Moore's law pushes digitization down to the lighting level. Over the past four decades, digitization and the advance of ubiquitous connectivity through standardization on IP-connectivity and the Internet have dramatically changed many domains, like e.g. telephony, consumer electronics, financial systems and retail. As the relentless law of Moore is still pushing down costs for both digital technology and connectivity, more advancements are to be expected in the coming period. It is forecasted that technology, allowing affordable connectivity of a large variety of ever smaller objects to the Internet, will become widely available. The digitalization wave has finally reached even the smallest and most cost sensitive devices, like door locks and light bulbs. Commercial examples on the market already now can be found e.g. in the Philips Hue™ system and connected door locks.

This development brings IP-connectivity to yet another scale as the number of items (things) is potentially much larger than that of the human related mobile telephones or personal computers. This trend is generally referred to as The Internet of Things (IoT) and analysts' predictions about the number of devices connected to the Internet vary between 20 billion [5] and an amazing 50 Billion [6] over the coming years. In this article we will explain how the inclusion of luminaires, in professional buildings like e.g. offices, in an IoT-infrastructure will facilitate existing activities, open up new opportunities and reduce integral cost.

We will continue this article with a short overview of the set-up and results of the OpenAIS project followed by a detailed discussion on the value and the advantages of the IoT-centric architecture compared to more classical lighting systems. We will describe advantages in (product) costs, development efficiency and availability of advanced services. The introduction of IoT as the backbone for connected lighting systems enables seamless communication and data sharing between devices ("things") hence enabling services across building related functions and beyond. Consequently, it will bring radical changes to the industries by converging multitudes of vertical markets.

These advantages will fall to companies in a variety of domains. In particular for the lighting industry IoT will provide opportunities to decrease both CapEx and OpEx costs by leveraging on commodity hardware, network and other software stacks. For facility owners and installers, it will offer higher efficiency in installation, maintenance and operation of buildings that can materialize in higher renting rates as well as opening up new markets of additional value add. Finally, the openness and standardization of the IoT-technology used, will attract and enable new entrants as independent vendors, integrating their offerings on top of the lighting infrastructure, without interaction with either the lighting company nor the facility manager.

The OpenAIS project

The OpenAIS project started in 2015 and ended in June 2018 and developed a solution for IoT connected lighting. OpenAIS is a cooperation between seven leading companies in the European Industry and two academic partners and was partly funded by the EU under the Horizon2020 program. The OpenAIS partners are Signify (formerly Philips Lighting), Zumtobel, Tridonic, Johnson Controls, Dynniq Belgium, NXP, ARM, Eindhoven University of Technology and TNO-ESI (see Figure 1).

From early 2015 until mid-2018 the consortium worked on many aspects of the lighting architecture for the 2020's. The project team developed a vision for the digital lighting in offices of the future, including a definition of the primary use cases for the evolving stakeholder field. Extensive market study and stakeholder interviews were important inputs into this study [7]. The project also studied the impact of the trend IoT-infrastructure on the entire value chain [8]. One of the cornerstones of the project was the definition of an architecture that was fully based on emerging IoT-standards. After an extensive state of the art investigation, a number of standard network technologies have been selected which are elaborated in an earlier article, [1] [3] some more details are described in the final architecture document [2]. The project also involved user studies in a modern and flexible lighting environment created by the project. These results are elaborated in [9] and in a subsequent paragraph. To support the actual implementation of OpenAIS, that relied on sometimes very new and immature technologies (see also ref [1] for more details on the execution of the implementation), OpenAIS also developed a number of supporting tools and techniques. This

included simulation tooling based on a Domain Specific Language allowing for a complete behavioral simulation of the OpenAIS system [10]. This tooling was also very important in the integration phase and the evaluation of problems enabling an almost 'digital twin' of the real control system at hand. Finally, the Eindhoven University of Technology evaluated by simulation the performance of the wireless technologies (Thread) deployed in the project.

In the summary of the project results in the next paragraph we will focus on two topics: the identified benefits in additionally created value and reduced costs and the architecture of the system. For the latter we will focus on the specifics of its integration in the Internet of Things.

Figure 1: The OpenAIS consortium.

Summary of the OpenAIS project results

Scenarios and use cases, the added value of OpenAIS

The results of the OpenAIS project are described in [7] Through in-dept interviews with a large variety of stakeholders in the value chain, the OpenAIS team has identified the scenarios and use cases that bring significant benefits for stakeholders and that are enabled by inclusion of lighting in the IoT. These scenarios and use cases are summarized in Three "Super Scenarios":

A. Increase Building Value:
In the changing world of office space, provision owners will need to make their properties more attractive for businesses to lease or rent. The industry of professional buildings is aiming at "Trophy workplaces" making visits to the office a luxurious and rewarding experience.

B. Building Wide Ecosystem:
Luminaires are everywhere where people are and if these luminaires are connected to the Internet, they can be leveraged as a valuable infrastructure for services in the building beyond illumination. In the future, systems in a building will be expected to share sensors and seamlessly interoperate to the benefit of the building and their stakeholders.

C. Easy Life:
A solution that brings advantages for those who prepare, install and maintain a lighting installation. The solution should be easy to specify, design, install, commission, operate and maintain without making compromises on the ease of use.

OpenAIS Architecture

The OpenAIS architecture has been constructed according to the principles described before: 1) Including the lighting control system into the Internet of Things infrastructure, 2) leveraging as much as possible of emerging standards and ecosystems and 3) creating an open standard allowing mix and match of different vendors. The main components in the architecture are the object model and the selection and integration of an IoT-framework. A more detailed description of the OpenAIS architecture and object model is given in ref 2 and 3. In this paper we restrict ourselves to a short description of these two main elements.

IoT-framework integration

After a state-of-the-art investigation (in 2015) OpenAIS selected Lightweight M2M (LWM2M) defined by the Open Mobile Alliance (OMA) version 1.0 as the basis for the OpenAIS architecture. At the moment of definition of OpenAIS, LWM2M was one of the few alternatives that had a released specification and implementations on the market already. LWM2M supports device management and defines the protocol between the resource-constrained field devices and a LWM2M-Server. This defined protocol is optimized for constrained field devices and limited band-width usage. Underneath LWM2M OpenAIS fully relies on standard "internet" technology, with IPv6-based communication, UDP as the transport layer and the CoAP protocol, defined especially for use in

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the domain of constrained embedded devices. Security is enabled by the combination of both transport (DTLS) and application layer (OSCORE) encryption.

Where the goal of building the architecture fully on (emerging) ecosystems has been nearly achieved, OpenAIS had to fill one gap in existing IoT-offerings. All currently available IoT-frameworks focus very much on connecting field devices to the cloud only. However, lighting systems in professional buildings have the unique requirement of high speed, low latency, secure and reliable communication between large sets of on premise devices. Within the OpenAIS project an Open Group Communication (OGC) protocol was specifically developed for this purpose, supporting IP communication between many local devices with very short response times. The OpenAIS architecture can work with any (wired or wireless) network that supports IPv6.

OGC is a key innovation of the OpenAIS Architecture, that allows to deliver lighting commands to many controlled light points in parallel without noticeable latency. In addition to resolving the latency and scalability issues, OGC provides the base for an elaborated out-of-the-box operation that supports the electrical contractor best and induces operational compatibility across different IoT frameworks and their (future) versions. Using OGC a low latency local “group agent” for User Interfaces and distant (e.g., cloud based) control is made available, that also provides the needed fast response and resilient operation of the lighting when the connection to cloud control is lost or slow. These principles are applicable to support other building controls services in the future, and we expect they may be picked up once also the BMS services start moving towards an open CoAP / IP based architecture.

Object model

Investigations showed that existing public models like available in IPSO were too limited for advanced high-quality lighting control and simple integration of lighting into BMSs. For the application layer of the OpenAIS project, a dedicated Object Model was developed, optimized for the identified future scenarios and use cases. This object model contains 19 newly defined objects that are added by OMA Specworks to LWM2M (objects 3387–3406). This OpenAIS application layer is based on the well-known Control, Actuate, Sense model. On top of this OpenAIS has added a data Collection object supporting the ever-increasing role of lighting as an infrastructure for a large distributed sensor network. The OpenAIS Object Model is created as a RESTful architecture [2]. Examples of user required features that came out of the stakeholder interviews and that are supported by the OpenAIS Object Model are Tunable White and built in redundancy and recovery.

Architecture verification, the large-scale pilot in the White Lady building

The architecture has been verified by a full-scale office lighting system in the White Lady building (see Figure 2), including presence, daylight and user control at a real office space, also including smartphone control through user Apps and an Integration in a standard BMS- System [12].

Figure 2: OpenAIS prototype luminaires in the White Lady pilot site.

Advantages of IP connected lighting

Increased Building Value

One of the three leading themes in the requirements and value propositions developed for office lighting in the 2020’s is increased building value. With a battle for talent ongoing, offices need to become ever more attractive places to stay, in order to attract and retain a modern, very mobile work force. Offices could become “Trophy workplaces” where visits are experienced as a true luxury and a rewarding experience. All of this reflects back upon the building value and the (premium) price levels building owners can get from the market.

Light is one of the key elements that play a role in creating this value e.g. by adapting completely and automatically to the user needs and preferences, including the most up to date learnings from human centric lighting like e.g. Circadian Rhythms, task-oriented lighting, the use of color, increased light levels for seniors or people with a visual handicap (e.g., color-blindness or night-blindness) and the like. This amongst others requires context awareness of the lighting systems that is enabled by the introduction of sensors in the lighting infrastructure. The OpenAIS system supports integration of various types of (new) sensors easily on its infrastructure by using standard IoT-infrastructure and IP-connectivity (wired and wireless). Example of such sensors next to the classical occupancy detection are sensors for measuring the air quality, noise level, number of people present, walking trajectories etc. It is expected that architectures like OpenAIS will play an important enabling role in certifications like the WELL standard for buildings [13].

Another aspect of “value” involves the presence (and experience) of user control [14]. Although a fully automatic, user-following bubble of preferred settings, adapted to time of day, external light levels and tasks is the ultimate goal of such a context aware system, users demand the feeling of control. So, user control is an important value even if it actually will be used less and less in the future when the full intelligent building promise materializes. As an intermediate step, technologies are applied, that enable smart phone apps to act location aware. The user adaptations of the light settings, according to personal preferences, can then automatically follow the user when moving through the building. The integration of the OpenAIS lighting system with the traditional IT-infrastructure in the office allows the reuse of standard infrastructure for user access (the local Wifi including all security and authorization functionality). The OpenAIS system therefore easily supports (and at limited investment levels) user adjustment of the lighting to own preferences with smart phone or other mobile devices. Preferences included are e.g. the light level, color temperature or directionality.

The openness and suitability of the OpenAIS architecture has been further proven in the White Lady project by the fact that parties, outside the group of lighting vendors and installers, developed user control applications allowing various levels of individual and group control including interaction between people and settings. Personal light control by an app that runs on various types of mobile devices has been implemented and publicly demonstrated by the OpenAIS team in the pilot in the White Lady building in Eindhoven, the Netherlands.

As part of the OpenAIS project, the appreciation by office workers has also been validated in the pilot that ran in a real operational office building in Eindhoven, the Netherlands [9].

Another aspect in increasing the building value through the introduction of IoT-based lighting systems is the ease of integration on data and control level with value added services and other verticals in the building that currently are hardly accessible or costly to integrate. As part of the OpenAIS architecture, Data Collection is a primary function implemented in the system. This mechanism allows the collection of data from many sensor streams, pre-processing, intermediate buffering and forwarding to cloud/back-end services. Usage of standard technologies from the I(o)T-domain allows to implement this using standard building blocks like Linux based gateways that seamlessly fit into the OpenAIS system. Data collection and forwarding to the Johnson Controls Metasys BMS system has been used to validate this advantage of the architecture

The integration of sensors and the accessibility of their data opens the integration of many additional services on an IoT-based lighting system. As an example of these, the occupancy detection sensors that are integrated in the luminaires can be reached via IP and hence the presence data are available for authorized apps. This yields precious information about the use of the building that enables to adapt the services accordingly. For example, cleaning schedules can be optimized according to actual use of the system, elevators can be directed to floors where many people are moving in corridors and the ventilation can be adapted to the number of people present in a space. These data can also be used for on- and offline optimization of the building, usage of workspaces, finding empty desks or empty meeting rooms. One could even develop an app to find a colleague in a building. IoT connected lighting can further help easily provide the information to achieve certifications such as BREEAM or LEED by increasing the building performance rating and reducing the carbon footprint.

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Adapting the building lighting control systems, after installation is usually a costly endeavor that requires the original vendor (if still available) and a retrieval/establishment of the current status and configuration of the installation. IoT-based lighting systems offer through their open interfaces the ability to extend and modify the system without all of this, including the extraction of current configurations from the field devices. In the OpenAIS architecture document [2] various mechanisms as defined by OpenAIS are described that allow such extensions of functionality through well-defined standard mechanisms. Interfacing with the lighting system is possible through standard technology like e.g. web interfaces and allows for remote access.

As an example of this extensibility the OpenAIS project had a separate application implemented by a party independent from the consortium's lighting manufacturers that controlled the lights in the building as a demonstration for the Glow festival in Eindhoven [15]. In this demonstrator the lights of the White Lady building where flashed as a running light at night, clearly visible outside to the visitors of the festival. This application was implemented without any adaptations to the lighting system and fully through standard IP-based interfaces. A movie of this can be viewed on YouTube [16]. Figure 3 is a picture of the demo in action.

Figure 3: OpenAIS demo at Glow.

A Building Wide Ecosystem

Lighting is everywhere in a building where people are, so any infrastructure to control lighting, is inherently distributed throughout the entire building. Hence it is economically sensible to share this communication infrastructure with other functions that also provide services in the building, e.g. heating/cooling/ventilation, access control, window blinds and the like. This can significantly reduce the costs for additional applications, that just need a number of sensors installed.

Above the direct sharing of the physical communication layer, the standardization on IP opens up a realm of further integration potential. The architecture with application neutral IP-based communication systems and with open (standardized) object models and API's, allows seamless data-integration across today's application silo's. Open API's pave the way for multiple parties to provide services and products for specific needs, building upon already present infrastructure and data streams.

A first major step for a Building Wide Ecosystem is integration of the lighting IP network with the BMS. The OpenAIS pilot in the White Lady building in Eindhoven has shown the feasibility and benefits a seamless integration between the lighting system and BMS offers. The architecture of the OpenAIS system based on standard IoT-technologies has allowed to implement such a link using standard webservices in a development-friendly and off the shelf Linux domain, with a limited effort. An important consideration in this is also that no changes to the core lighting system and field devices were needed to realize this link. Figure 4 shows a floor plan of the OpenAIS pilot, with indicated in blue where PIR sensors perceive presence of people. The OpenAIS architecture made this sensor information continuously available to the BMS. In future deployments of this system this information can be used for purposes other than illumination e.g. the heating can be optimized. Beyond direct control applications it can provide information to the building manager about the usage of the building, hence enabling fact-based decisions about adaptations.

The development of the communication structure for such a Building Wide Ecosystem is further facilitated by the Fairhair Alliance [17].

When the building wide ecosystem widens, and multiple applications become available and share information through standardized interfaces, new entrants outside the current industry will enter and add value to either the existing parties or even directly to end users. Due to the restricted, scattered and proprietary settings in current buildings this is a non-existent market as of today. OpenAIS has not piloted this approach with

parties external to the consortium as that was not feasible in the set-up of a European project. Yet the applications developed by the Eindhoven University of Technology to control the Lighting system and collect its data only through standard interfaces is already a solid example of the offerings that will be enabled by an IoT-based architecture.

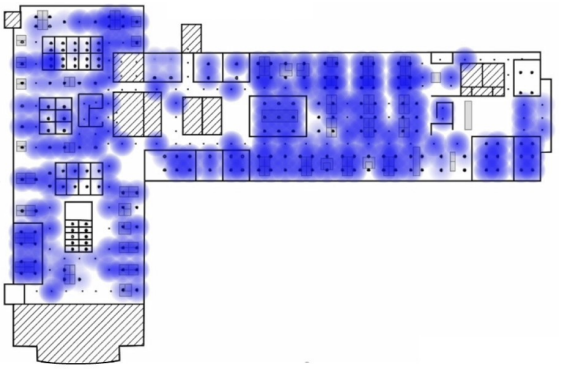

Figure 4: Floor plan of the OpenAIS pilot building. Indicated in blue where presence sensors are triggered.

Easy Life

Within the OpenAIS project the “Super Scenario Easy Life” was defined as the set of use cases where the life of (lighting) designers, installers, operators and engineers is made easy by the conversion of the Lighting Control System to an IoT-infrastructure that supports IP communication to each end point: the luminaires and sensors. IP will cater for simplicity in specification, design, implementation and operation and in addition for security measures one can rely on. Open API’s allows adding advanced applications to a lighting system after installation. We will now discuss the results and advantages for the various parties in the chain as indicated in this scenario.

Starting at the R&D side, the obvious and often quoted advantages of digitization are also prominently reflected in the OpenAIS approach:

Availability of standard components: Reuse of common infrastructure, platforms and technologies drives down the R&D effort in digitized domains. Standard CPU’s running standard operating systems like Linux and/or Arm Mbed and platforms for communication, software download, device management and security (LWM2M, Arm Mbed) avoid extensive (and costly) lighting-specific developments and especially maintenance. New connectivity standards, security updates and new functionality has come available through (free) updates of the basic platforms even over the short lifetime of OpenAIS already.

Availability of skilled Reserch and Development staff: Development personnel is much more abundant when making use of the large standard platforms indicated above, especially compared to the use of lighting or even vendor specific technologies. This especially applies to the maintenance phase and the long tail, think of outsourcing, that can be a burden when proprietary solutions have to be maintained.

Reduced integration cost: With many verticals and proprietary building systems active in a single building, each individual deployment of a system may require involvement of key development staff from the lighting vendor. As such hampering the scalability of business execution and overloading valuable resources that should be invested in created additional value propositions and functions.

In summary, the lighting industry will (and in OpenAIS already does) benefit from IP connected lighting as the standards for networking, commissioning, SW updates and maintenance are developed and maintained by the IT industry, that is much larger than the lighting industry.

Also, for the installation and maintenance side the advantages of this move are significant;

IoT-based lighting systems can be installed and tested as a part of the much larger IoT-network, making use of off-the-shelf tooling and technology. Already in the OpenAIS pilot standard IT-tooling was used to analyze message traffic, performance bottlenecks and network load.

The use of Power Over Ethernet networks combining power and communication does furthermore reduce mains installation requirements, lowering the need for specialist personnel and potentially combining lighting installation activities with other IT-installations.

Using a wireless IP connectivity to the end node (e.g., Thread) also gives the advantage of using existing IP tools for integration in the IP infrastructure of an office, allowing also the same

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node-to-node and OGC communication as for wired network.

Already in the commissioning phase the advantages of the use of standard IoT-based lightings systems are evident. Tooling to be used to commission devices can be built upon the facilities of the frameworks used (e.g., like LWM2M as used in OpenAIS). It is expected that in future these systems will grow in functionality and adaptation. Probably standard tools will emerge, to commission multiple types of devices from a single application. Standard network technology also there is an advantage, as soon as connectivity is established controllers can be accessed through an IP connection and hence groups of luminaires to be controlled by a certain switch, timer or app-related action can be easily adapted. With the introduction of BIM (Building Information Modeling), luminaire IP addresses can be coupled to their location in the building, which reduces commissioning efforts. BIM can also make life easier during the design phase.

IP connected luminaires will provide detailed information about an internal status and failures to maintenance engineers, so that they can go on site knowing what to do and bringing the right replacement parts. In the OpenAIS system the status of all devices was made available over an IP connection to the BMS -system as a proof-point for such integrations. Also, other maintenance dashboards and tools could easily integrate this in the future. Figure 5 shows the floor plan of the OpenAIS pilot where the time that luminaires have been on since installation is indicated. This facilitates maintenance of the luminaires (as the luminaires in the OpenAIS pilot were installed recently, the grey-scale in the figure is adapted for demonstration purposes. In reality, all luminaires are in the very beginning of their life-cycle).

Prepared for the future

IP connected systems are inherently prepared for future innovations: once IP connectivity is guaranteed, new innovative features and apps can be added to an existing system through SW updates via the network. With IP communication present, innovative features and apps can be created and added to existing lighting systems. An example of this is to add a new sensor to a luminaire that had a presence sensor only when it was installed. New sensors can for example measure temperature or CO_2 content in the air

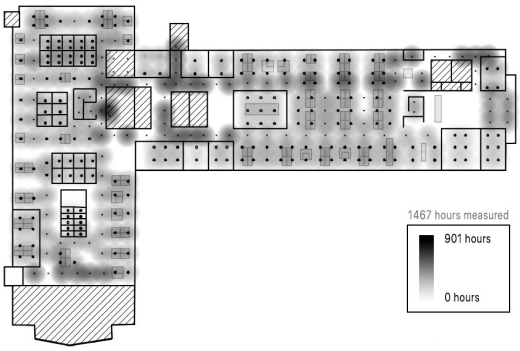

Figure 5: Floor Plan of the OpenAIS pilot where the grey-scale indicates the on-time of the luminaires since installation (scale is not realistic; none of the luminaire is close to the specified end of life).

and be installed in luminaires because of their omnipresence and availability of LV dc power and IP connectivity. The sensor can be approached and used for example by the heating or ventilation system.

In summary the main pillars below the move to IoT connected lighting systems are not different from those that can be found in other industries that are converting or have completed such a move to the digital domain. Reuse of an ever-expanding ecosystem which offers many of the basic components at a very low price with very limited development effort, speeds up developments enormously while reducing both product as well as development cost. The scale of these platform guarantee “automatic” innovation and improvements and the wide availability of skilled engineering force.

Conclusions

OpenAIS has proven that an architecture for (professional) lighting systems can be based upon the quickly developing technologies for IoT-infrastructure. OpenAIS has addressed the topics where professional indoor lighting differentiates from commonly existing IoT systems and dealt with the gaps existing at the conception of the project and architecture [18]. It is expected that some of these gaps will be filled by ecosystem developments over the coming years. OpenAIS also has been firmly pushing some of its findings and innovations to related standardization bodies, building on an IoT-infrastructure that will fully serve the lighting industry. Based upon this architecture the OpenAIS team has developed solutions to include luminaires in IoT and fulfill the

use cases of the 2020's as defined in the requirements phase of the project.

Building a lighting system based upon IoT-technologies provides significant benefits during the design, preparation and maintenance of lighting installations. The omnipresent network of IP connected luminaires will serve as an infrastructure for multiple beyond lighting sensors and devices and being based on standard network technologies and OpenAIS enables new applications and even new application domains. The project and its pilot have validated the main predicted benefits in the areas of: 1) increasing building value by enabling many new and flexible applications for lighting control and beyond, 2) Enabling a building wide ecosystem by using the lighting infrastructure as a backbone and by standardizing on IP based communication with open API's and 3) By increasing the "ease of life" for development, installation and maintenance by reducing costs and facilitating new levels of functionality.

Acknowledgment

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References

[1] Integrating Lighting in the Internet of Things, Frank van Tuijl and Ben Pronk, LED Professional Review 67 | May/June 2018
[2] Final reference architecture of OpenAIS system, OpenAIS deliverable D2.7, (www.openais.eu/en/results/)
[3] The Internet of Lights: An Open Reference Architecture and Implementation for Intelligent Solid State Lighting Systems (E. Mathews, S. Guclu, Q. Liu, T. Ozcelebi, J. J. Lukkien) Energies journal volume 10 issue 8, 2017
[4] http://www.openais.eu. Update: OpenAIS Symposium presentations published, May 23rd in Eindhoven
[5] https://www.gartner.com/newsroom/id/3598917
[6] Mc Kinsey — Lighting the way — September 2012
[7] Report on selected scenarios and use cases, OpenAIS deliverable published via the OpenAIS website www.openais.eu/en/results/
[8] The Impact of the Internet of Lighting on the Office Lighting Value Network (T.C.F. van de Werff, H.A. van Essen, J.H. Eggen), Journal of Industrial Information Integration, Jan 2018
[9] Evaluating User Experience of Dimming Control over Office Lighting (T.C.F. van de Werff, C. v. Lotringen, H.A. van Essen, J.H.Eggen). To be submitted to CHI '19
[10] "Virtual Prototyping of Large-Scale IoT Control Systems Using Domain-Specific Languages", Jacques Verriet (TNO), Lennart Buit (TNO), Richard Doornbos (TNO), Bas Huijbrechts (TNO), Raymond Kerstens (TNO), Kristina Ševo (Philips Lighting), Jack Sleuters (TNO), Mark Verberkt (Philips Lighting). Submitted to proceedings of MODELS2018 conference
[11] Choosing your IoT Programming Framework: Architectural Aspects (L.F. Rahmani, T.Ozcelebi, J.J. Lukkien), IEEE FiCloud'16
[12] IoT System Architectures of BMS, LMS and BIM, John A. Sayer, 7th International LED professional Symposium, 2017
[13] http://standard.wellcertified.com/light
[14] Share and Share Alike? Social Information and Interaction Style in Coordination of Shared Use, Karin Niemantsverdriet, Thomas van de Werff, Harm van Essen, Berry Eggen, CHI Conference on Human Factors in Computing Systems, 2018
[15] https://www.gloweindhoven.nl/en
[16] https://www.youtube.com/watch?v=c5NuvptlGVg
[17] https://www.fairhair-alliance.org/about-fairhair/what-is-fairhair.html
[18] Challenges of the Integration of Lighting Systems and Components in IoT, by B. Pronk and S. Verbrugh, Signify, LED Professional Review 68

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Simulation Techniques During the Development of an LED Driver

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Abstract

Every LED driver is composed by one, two or sometimes three different topologies based on power electronic components: magnetics, MOSFETs and DIODEs working under hard conditions. The electronics reliability is limited by the stress that these components are able to support.

More and more, LED drivers are demanded with a wide range of output power, so the operation of this kind of topologies integrated in LED driver has many variations far away from its optimal design operation. This is specially critical in topologies like LLC resonant topology (going out of ZVS operation or third resonance problems) or Power Factor Corrector Booster topology (increasing switching power losses due to very light load operation).

Guaranteed reliability without an over-cost in materials involves a fitted development by means of optimal magnetics design and knowing the behaviour of that topology in all range of the LED driver operation.

Using topology simulations, magnetics involved in the LED driver can be designed in an optimal way, fitting them into the application. Using this way of design, all functional parameters, such as frequency operation or Duty Cycle can be estimated and fixed in final application. It is specially interesting if we may foresee Conducted Electro-Magnetic Interferences by setting switching frequencies.

Also, this method provides all information about electrical parameters like voltage or currents through components, allowing the engineer to estimate power losses and how are they distributed on the circuit, in all components. In addition, power losses can be distributed in a regular way between transformer and semiconductors or between wire and core in a transformer in order to find the maximum efficiency allow in the application, achieving the best trade-off.

Most of simulation models have been developed in State-Space apart from LLC topology. This is because of the First Harmonic Approximation (FHA design method), since it doesn't fit enough with the model of an LLC resonant topology in a constant current LED driver application, including a wide output voltage range. Also, LED load for the constant current LED driver in LLC simulation must be calculated in every point of LLC resonance, following its gain behaviour.

In conclusion, simulating topologies during the design process of a LED driver can provide the necessary analytic tools to estimate functional parameters, electrical parameters, power losses and efficiency by fitting the magnetics. Thus, product reliability might be maintained without producing a component over design, and so its corresponding over cost.

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Introduction

LED Driver market has the trend of reducing prices without renouncing quality. In order to reach that goal, LED driver designers must fit their power electronics designs in order to reduce material costs in final products. Furthermore design investments associated to the time required to make the product should be reduced and optimized. These requirements involve many aspects during designing process, but the principal condition to reach that, is fitting the topology (or topologies) to the application. That condition is necessary but not enough to have success in the design process.

In this paper, simulation techniques are presented due to the benefits during the design process optimization. These topology's models allow to fit the topology to the desired application, predicting electrical and functional parameters and anticipating the characteristics required by the transformers or bobbins, semiconductors or even EMI filters. Most of these models can be used in freeware like SCILAB, LTSPICE or ORCAD PSPICE LITE.

In order to resume different techniques, three mostly used topologies are going to be described: Boundary Discontinuous Mode Booster, Flyback and LLC resonant topologies. Certainly other topologies like Buck converter or Continuous Mode Booster topologies can be modelled too, but they aren't so representative in LED Driver's topologies.

Booster Topology

However making a State-Space model of Booster topology is quite simple, Booster Topology doesn't need simulation model to predict functional and electrical parameters. Behavioural equations, described in most of Booster Application Notes, are enough to design a Booster topology considering power losses in the bobbin and the semiconductors. Programming these equations with different functional configurations (Output Wattage – Input Voltage) allows us to compare different booster designs behaviour to select which one fits best in our requirement, as is shown in Figure 1.

Based on behavioural equation simulations, frequency switching operation can be fixed for a specific input voltage and output power. This is

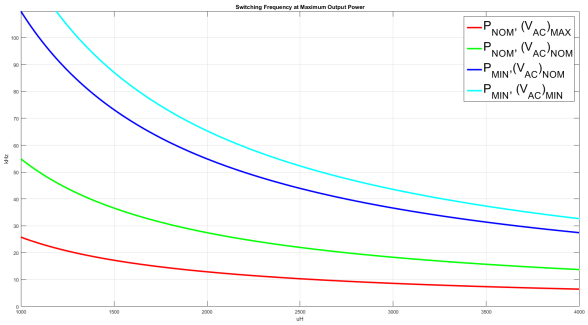

Figure 1: MOSFET switching frequency vs Bobbin Induction at different mains voltage values.

especially interesting to reach conducted emissions without overdesign EMIs filter. In the EN 55015=2013 standard, there are two abrupted steps loacated in 50 kHz (quasi-peak falls from 110 dB(µV) to 90 dB(µV)) and 150 kHz (quasi-peak falls from 80 dB(µV) to 66 dB(µV)).

Setting maximum output power switching frequency fewer than 50 kHz ensure not to over cost EMI filter due to standard level. It applies to third harmonic of the commutation, which it will be under 150 kHz Step-Down standard level. An example is given in Figure 2, where the effect of the correct Bobbin Inductance value is shown, avoiding over design EMI filter increasing X2 Line to Neutral capacitor (Booster noise emission is mostly in differential mode). Increasing these capacitors have negative effects in Power Factor value and in EMI filter cost.

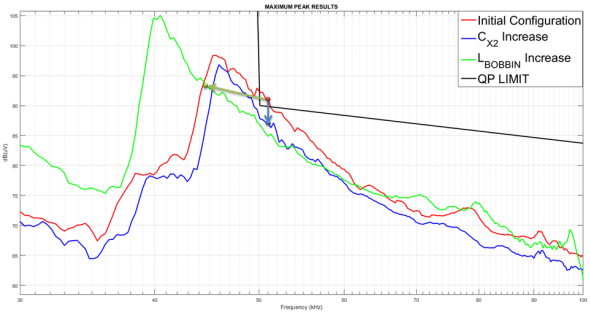

Figure 2: EMIs compliance example.

In conclusion, decreasing switching frequency has positive effects in conducted emissions. But in the other hand, bobbin size has negative consequences: Decreasing switching frequency involves increasing inductance. For the same output power a higher inductance requires a higher number of wire turns, which produce a higher wire power loss or a higher effective area in the core, increasing ferrite power losses. Both situations involve increasing bobbin coil former size.

For reaching a minimum bobbin size without reducing efficiency, bobbin and semiconductors power loss characterization must be done. From behavioural equations, all electrical parameters necessary to estimate power losses can be extracted. In the bobbin, copper wire resistance can be modelled using skin and proximity effects due to continuous resistance and ferrite loses using Steinmetz equations. MOSFET and diode conducted and switching power losses are well defined in many Application Notes.

Programming power loss equations due to behavioural equations allows us to estimate higher efficiency topology due to minimum bobbin size, letting us to compare different bobbin sizes and different MOSFET & diodes devices under same conditions, as are shown in Figures 3, 4. 5 and 6. Simulating these parameters allow us to reduce the number of iterations in the bobbin design at the same time that it is fitted to our application. It also allows us to compare different core ferrite materials, selecting the most optimal bobbin constructive parameters to our application.

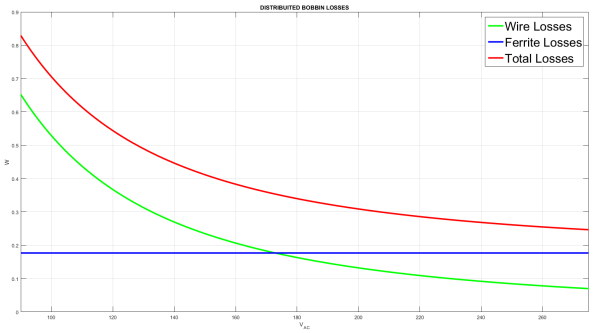

Figure 3: Bobbin power loss estimation.

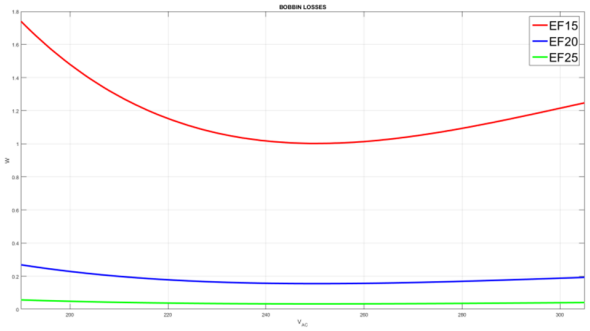

Figure 4: Bobbins Comparison.

In conclusion, programming these equations allows us to set frequency switching to avoid EMI filter over cost, finding the minimum bobbin size and selecting the appropriate MOSFET device to reach as highest efficiency as possible.

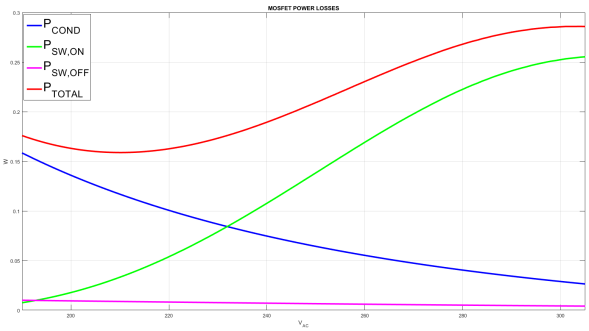

Figure 5: MOSFET Power losses estimation.

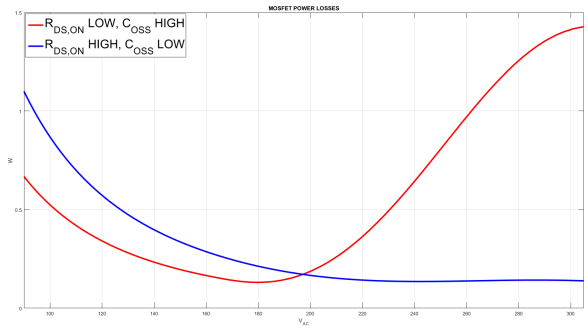

Figure 6: MOSFET devices comparison.

Flyback Topology

Flyback topology is usually used in two modes: Firstly as DC-DC power converter after Booster topology in a two (or three) stages into the driver, and secondly in a single stage driver, replacing Booster bobbin for a Flyback transformer with a power factor correction control. In a single stage, Flyback controlled with a power factor corrector is close to Booster topology. Behavioural equations can be easily modified in order to include transformer turns relation. Once you have these Flyback equations programmed, the design processes due to the goals are the same.

For that reason, Flyback as second stage, with a Booster voltage regulated by the PFC controller, will be considered in this article. For Flyback characterization, a non-linear State-Space model has been created. This model has three linear “sub-models”, as are shown in Figures 7 and 8.

State-Space model has four State-Variables: Inductances involves currents through their winding and capacitors involve their own voltages. Some states make some variables to be zero (like iSEC when diode switches off). It makes that some matrix is going to be singular, and then, they cannot be converted in discrete matrix. This problem can be avoided making that the program, which is running the simulation, uses the proper State-Space matrix depending on Flyback state.

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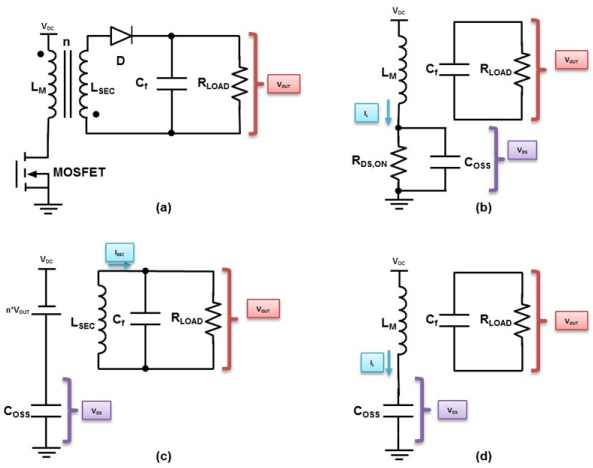

Figure 7: Flyback Topology Modelization:(a) Flyback Topology; (b) MOSFET ON and Diode OFF; (c) MOSFET OFF & Diode On; (d) MOSFET & diode OFF.

$$(a)\ \frac{d(i_m)}{dt}=\frac{v_{L_M}}{L_M};\quad \frac{d(i_{SEC})}{dt}=\frac{v_{L_{SEC}}}{L_{SEC}}=\frac{v_{OUT}}{\frac{L_M}{n^2}};\quad \frac{d(v_{DS})}{dt}=\frac{i_{C_{OSS}}}{C_{OSS}}=\frac{i_{L_M}-i_{R_{DS}}}{C_{OSS}};\quad \frac{d(v_{OUT})}{dt}=\frac{i_{C_f}}{C_f}=\frac{-i_{R_{LOAD}}}{C_f}=\frac{-v_{OUT}}{C_f*R_{LOAD}};$$

$$(b)\ \begin{Bmatrix}\frac{di_m}{dt}\\ \frac{dv_{DS}}{dt}\end{Bmatrix}=\begin{pmatrix}0 & \frac{-1}{L_m}\\ \frac{1}{C_{OSS}} & \frac{-1}{C_{OSS}*R_{DS}}\end{pmatrix}*\begin{Bmatrix}i_m\\ v_{ds}\end{Bmatrix}+\begin{Bmatrix}\frac{1}{L_m}\\ 0\end{Bmatrix}*V_{DC};\quad i_{SEC}=0;\quad \frac{dv_{OUT}}{dt}=\frac{-1}{C_f*R_{LOAD}}*v_{OUT};$$

$$(c)\ \begin{Bmatrix}\frac{di_m}{dt}\\ \frac{dv_{DS}}{dt}\end{Bmatrix}=\begin{pmatrix}0 & \frac{-1}{L_m}\\ \frac{1}{C_{OSS}} & \frac{-1}{C_{OSS}*R_{DS}}\end{pmatrix}*\begin{Bmatrix}i_m\\ v_{ds}\end{Bmatrix}+\begin{Bmatrix}\frac{1}{L_m}\\ 0\end{Bmatrix}*V_{DC};\quad \begin{Bmatrix}\frac{di_{SEC}}{dt}\\ \frac{dv_{OUT}}{dt}\end{Bmatrix}=\begin{pmatrix}0 & \frac{n^2}{L_m}\\ \frac{1}{C_f} & \frac{-1}{C_f*R_{LOAD}}\end{pmatrix}*\begin{Bmatrix}i_{SEC}\\ v_{OUT}\end{Bmatrix};$$

$$(d)\ \begin{Bmatrix}\frac{di_m}{dt}\\ \frac{dv_{DS}}{dt}\end{Bmatrix}=\begin{pmatrix}0 & \frac{-1}{L_m}\\ \frac{1}{C_{OSS}} & 0\end{pmatrix}*\begin{Bmatrix}i_m\\ v_{ds}\end{Bmatrix}+\begin{Bmatrix}\frac{1}{L_m}\\ 0\end{Bmatrix}*V_{DC};\quad i_{SEC}=0;\quad \frac{dv_{OUT}}{dt}=\frac{-1}{C_f*R_{LOAD}}*v_{OUT};$$

Figure 8: Flyback State-Space Matrix Modelization:(a) State-Space Variables; (b) MOSFET ON & Diode OFF; (c) MOSFET OFF & Diode On; (d) MOSFET and diode OFF.

Another matter is MOSFET Drain-Source voltage V_{DS} limitation. Simulation results are showed and compared with waveforms measured in the transformer calculated using these simulation scripts, as is shown in Figure 9 and 10. Functional simulated parameters are quite close to measured parameters. Even stray parameter effect (resonance), where resonance capacitor can be just estimated, has a good approximation with reality, allowing us to make a good estimation of the topology behaviour. At this point, Flyback topology designing tools have been developed with the same advantages of Booster Topology.

When Flyback transformer is being designed, a couple of additional issues must be considered. Firstly, MOSFET Drain-Source blocking voltage will depend on transformer turns winding ratio, as shown in Figure 7 (C). Furthermore, over voltage on this voltage value produced by leakage inductance when MOSFET turns off must be treated. Therefore, knowing MOSFET drain-source family voltage limit is necessary to design Flyback transformer properly. In

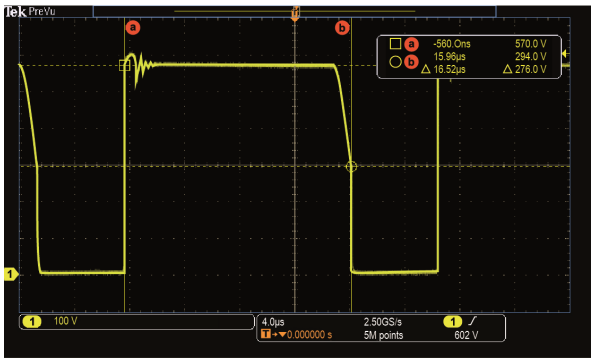

Figure 9: (VDS measurement screen-shot.

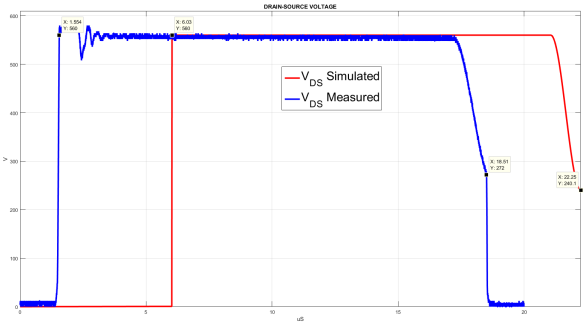

Figure 10: VDS simulation versus measurement waveform data vector.

conclusion, transformer turns ratio will be delimited by the relationship between maximum drain — source value, Flyback output voltage value, Booster output voltage and over 20–30% of maximum drain source voltage margin to ensure that over voltage won't be dangerous for the MOSFET.

$$V_{DS} = (V_{PFC} + n * V_0) * 1.3 < V_{DS_{MAX}} \qquad (1)$$

Secondly, power losses distribution into Flyback transformer has another parameter. Winding Area must be divided in primary side and secondary side. This distribution doesn't have to be 50% of the area for primary side and 50% of it to secondary side. It will depend of current density through both windings and the number of turns in each winding. The best way to determine which distribution fits better to the application is making multiple power losses characterization for the same situation with different distributions, as shown in Figure 11.

In Figure 11 power losses in different parts of transformer are shown. X-AXIS represents the percentage of winding area used in primary winding. As can we see, core losses are not affected by the windings distribution but wire losses and, in consequence, total transformer

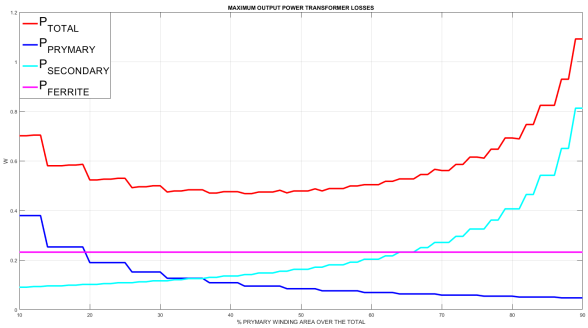

Figure 11: Distributed transformer power loss estimation.

losses are affected. Maximum efficiency is reached when primary winding power losses and secondary winding power losses have close values.

In EMI matter, setting Flyback MOSFET switching frequency is as important as in Booster topology. Stray capacitors make Flyback Transformer working as common mode noise generator, so a good attenuation in higher frequencies is required. Using low inductance common-mode filters improves stray values due to high frequency attenuation, moving resonance peak to a higher frequency, as Figure 12 shows. Common-Mode filter stray model has been done to compare an estimation of attenuation in both filters.

The way to reduce common-mode filter inductance to the minimum necessary is the same that Booster Topology. Setting Flyback switching frequency at maximum output power in a value where standard limit are higher allows us to reduce common-mode filter inductance, which involves a bit higher attenuation at higher frequencies and more alternatives of coil former shapes, as shown in Figure 12. It allows us to set the necessary common mode filter, without over designing it.

Resonant LLC Topology

Resonant LLC topology is the most complex topology modeled in this article. Most of design methods explained for this topology are based in First (or Fundamental) Harmonic Approximation (FHA). FHA is based in the assumption of the resonant current through primary is sine wave and it just has Fundamental Harmonic. So, based on that condition, all energy transferred to load is transported by this sine wave and a series of approximations can be done.

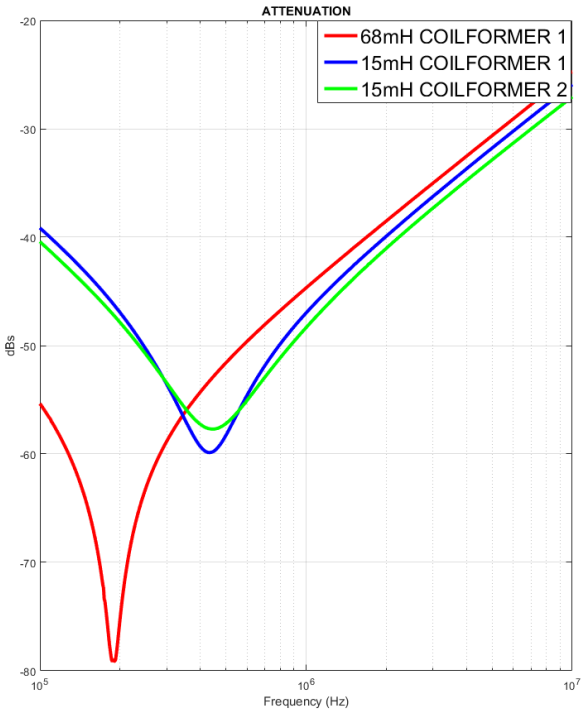

Figure 12: Attenuation Comparison of Common-Mode Filter of same manufacturer with different inductance of coil former shape.

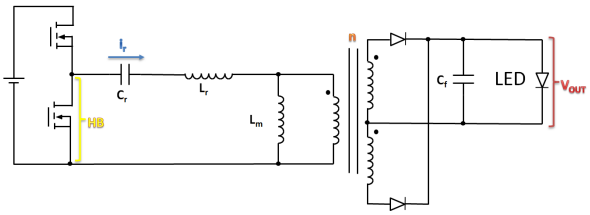

Figure 13: Tipical resonant LLC topology configuration for LED drivers.

However, this condition is just true when switching frequency of the half-bridge (Figure 13) is close to resonance frequency, which fits enough for constant voltage driver, where output voltage is constant. Switching frequency is dependant of output voltage, so output power variation has not effect over that parameter. Otherwise, output power variation has effect over resonant current peak, which is higher or lower depending on this power. A comparison between two output power conditions with constant output voltage are shown in Figures 14 and 15. Frequency remains constant (48 kHz) in spite of output power variation, but resonant current doesn't.

Nevertheless, FHA doesn't fit enough for constant current LED drivers. The reason is that the output voltage is not constant and it depends on the kind of LED load connected to the driver, the current value (Dimmable LED drivers), the temperature,

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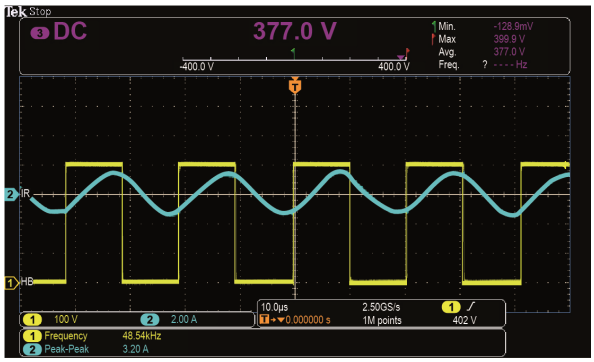

Figure 14: Constant Output Voltage (Ch3) Half-Bridge voltage (Ch1) vs Resonant Current (Ch2) waveforms in the same LLC topology at minimum output Power.

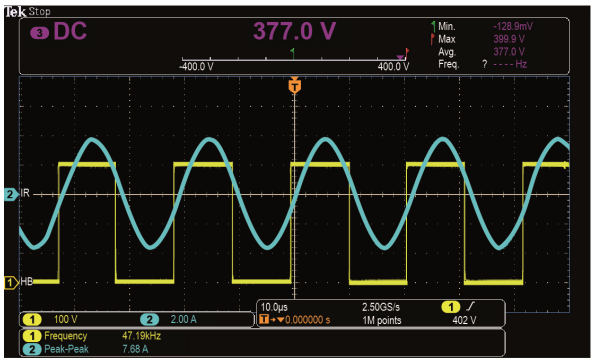

Figure 15: Constant Output Voltage (Ch3) Half-Bridge voltage (Ch1) vs Resonant Current (Ch2) waveforms in the same LLC topology at maximum output Power.

. . . Also, the higher output load admitted by the driver, the more polyvalent will be our LED driver.

One solution could be designing LLC transformer with constant voltage control, adding a third stage, such as an additional Buck or Buck-Boost topology, for making output current regulation. It has the problem of over cost in the final product due to reliability reduction by adding more components working in hard conditions. Other solution, which is going to be considered here, could be designing LLC transformer for a wide output voltage range.

In Constant Voltage LED Driver transformer design, a quality factor value is recommended between 0.4 and 0.6. However in Constant Current LED driver, gain slope versus frequency much be higher than in Constant Voltage in order to have as output voltage regulation as possible (Figure 16). Also, at nominal or maximum output power, switching frequency will be lower than resonance frequency, making that at nominal operation point won't be sine wave resonant current, as is shown in Figure 17.

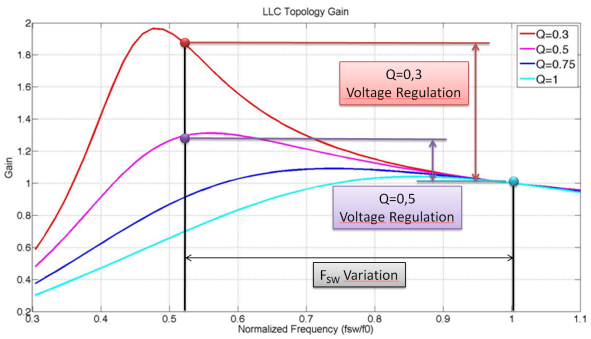

Figure 16: Gain versus frequency curves.

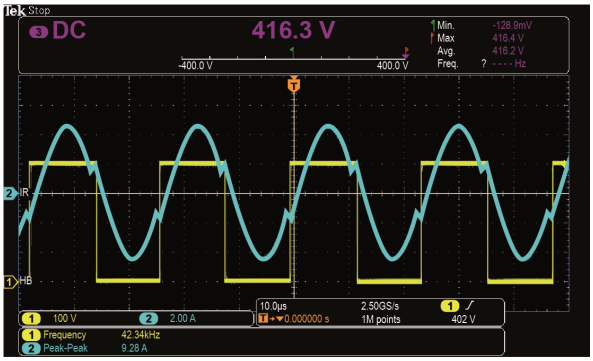

Figure 17: Half-Bridge voltage (Ch1) vs Resonant Current (Ch2) waveforms at lower switching frequency (higher output power).

In conclusion, FHA model is not useful for CC LED driver. LLC topology is not easy to make a model in State-Space. Most of State-Space models of LLC topology are based in FHA, too. The most powerful tool to make a model which represents output voltage gain versus frequency with LED load at constant current is SIMULINK. It has the advantage that you can program all simulations. It is useful also to characterize Constant Current load, which is such as a resistance dependant of Half-Bridge switching frequency.

However, SIMULINK with correspondent toolboxes costs are too high just to make LLC simulations, making an over cost in development process, increasing the necessary investment. To avoid that, LLC topology with constant current control can be developed in freeware based on SPICE models, such as LTSPICE or ORCAD LITE. Both programs, based on the same simulation method, returns same results of simulations. In Figure 18 and 19, a comparison between reality and SPICE simulation can be done.

Despite of the fact that it is not possible to make a

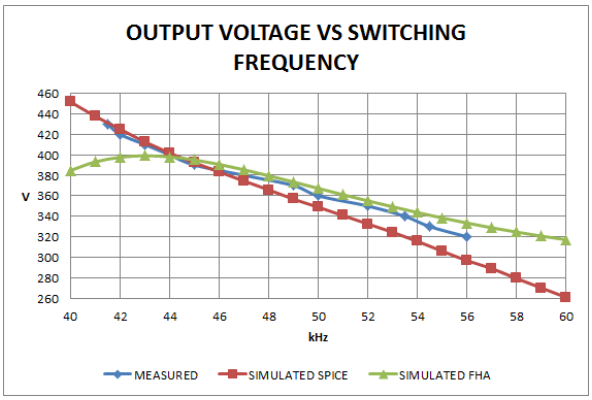

Figure 18: Output Voltage comparison between real measurement and simulations based on SPICE.

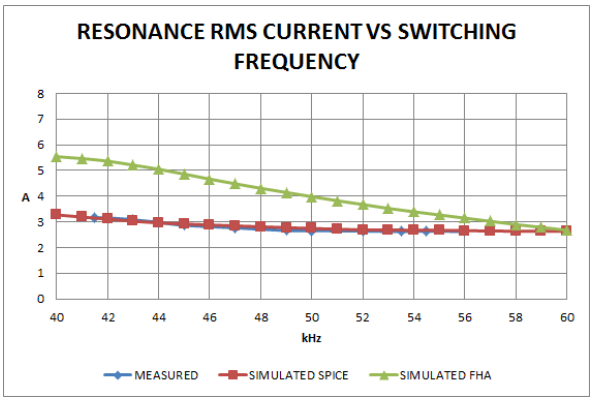

Figure 19: Resonant Current RMS value comparison between real measurement and simulations based on SPICE.

program for managing different simulations, these tools have the possibility of making parametric simulations, making multiple simulations while varying frequency. Also it allows us to make mathematical operations of vectors such as Root Mean Square or peaks detector, which can be exported to a table data.

With these data, optimal transformer design can be done taking the same considerations such as Flyback transformers. Frequency behaviour can be estimated in order to fix the transformer with the application without losing Zero Voltage Condition (ZVS) within the operation area. It involves a lot of penalty in efficiency, so power losses distribution must be considered. With the exportable information from SPICE simulation, power losses distribution can be done. In conclusion, setting switching frequency has the same benefits than Flyback transformer.

Talking slightly about SPICE model, Constant Current load modeled in a constant current model is quite easy in LTSPICE, using the predefined block Independent Current Source — Load, which is configurable. It is available in “Sym” library. In ORCAD LITE, this load can be modeled creating a “variable resistor”, which depends of output voltage value. These kinds of resistors automatically change their value to fix a predefined current. It is made by using blocks contained in “ABM” library. Both models are shown in Figures 20 and 21.

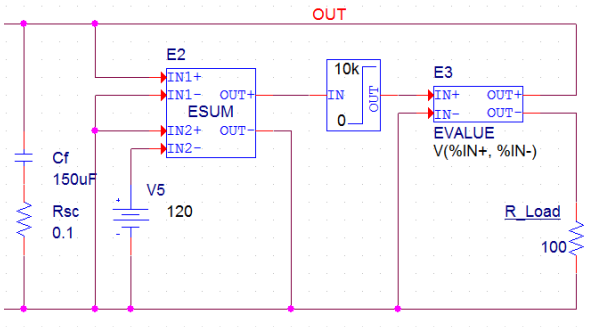

Figure 20: LED load at Constant Current mode model in ORCAD.

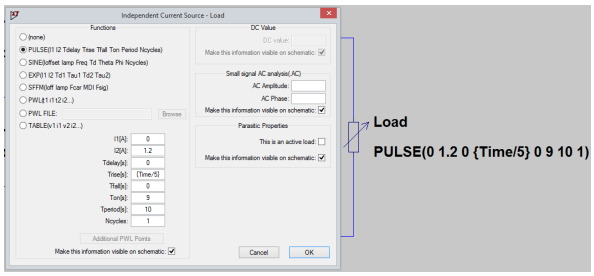

Figure 21: LED load at Constant Current mode model in LTSPICE.

Conclusions

To sum up, for every kind of topology, a model simple based on equation or simulation tools can be done without the necessity of make a high investment. In this article, three mostly used topologies used in Constant Current LED driver have been exposed. Every topology has their own process of modelization, depending of topology complexity.

Also, make this investment of time used developing these models has a quickly return every time it’s needed to design some transformer or bobbin for a new application by the reduction of the topology designing time, the number of iteration and the cost of material. Global benefits for this process are:

- Reduce designing time due to the number of iteration.

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- Fitting the new transformer design with the best coil former suitable for it.
- Efficiency optimizing of the topology, comparing transformer power losses with semiconductors power losses.
- EMIs filter optimization associated with switching frequency selection.
- Reliability increasing associated to design taking care about components limitation in the beginning of design process.

In conclusion, making simulations to make estimations due to hardware development could reduce designing time, material and investment costs, and increase reliability.

References

[1] AN2761 — Solution for designing a TM PFC based on L6562A.

[2] SLVA061 — Understanding Boost Power Stage in Switchmode Power Supplies.

[3] Zeljko Ivanovic, Branko Blanusa, Mladen Knezic. Power Loss Model for Efficiency Improvement of Boost Converter. Faculty of Electrical Engineering, Banka Lunka, Bosnia and Herzegovina

[4] Texas Instruments. Under the Hood of Flyback SMPS Design. SEM1900, Topic 1. 2010.

[5] Bo Yang. Topology Investigation for Front End DC/DC Power Conversion for Distributed Power System. Blacksburg, Virginia, 2003, ch4, ch5.

Latest Development of Drivers | Control and Dimming

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Abstract

The number of controllable light systems is expected to increase rapidly in the coming years. The LED driver is a vital component in a luminaire, as it enables control and dimming of the light output. However, the LED driver characteristics, especially its output current, efficiency, power factor, THD, and flicker, are not always characterized across dimming in manufacturer data sheets. Knowing the behavior of these electrical performance metrics when dimming is important for high quality luminaire and controllable light systems, as well as future internet of things, tunable white, and human-centric lighting systems.

This paper presents an automated test setup for LED drivers that enables an electrical performance investigation and characterization of the dimming behavior of commercial LED drivers. The output current, efficiency, power factor, THD, and flicker are measured across dimming with either 1–10 V or DALI dimming control. A total of 30 LED drivers are considered in the investigation, and their measurement results are compared and discussed.

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Introduction

While control is already in use in many lighting applications today, the share of controllable light systems and the extend of the control applied are expected to increase significantly in the coming years. One of the main motivators to apply control to lighting systems is the energy savings that can be achieved without sacrificing user value. The efficacy of light emitting diodes (LEDs) has increased rapidly over the last few years, but most forecasts imply that the efficacy will stabilize at around 200 lm W^{-1} [1]. The next important area for energy efficient lighting will therefore be intelligent and user-oriented lighting controls. In an efficient lighting system (indoor as well as outdoor) that includes occupant detection and daylight harvesting, the energy savings can amount to up to 70% [2]. Another motivator for controllable lighting systems aligns with the increased focus on internet of things (IoT), tunable white, and human-centric lighting that all require connectivity and control. The main enabler for above benefits is the ability to dim the light output of the LEDs by control of the LED driver (power supply). Figure 1 shows a series of dimmable driver concepts for various luminaire, in-track, or linear lighting applications. However, dimming of LED drivers introduce challenges to be considered when specifying new controllable lighting systems [2].

Figure 1: Various LED driver concepts including in-track as well as linear and compact standalone.

This paper aims to describe the various types of dimming and their effects. Of particular focus is how the driver-specific electrical performance parameters such as output current, efficiency, power factor, total harmonic distortion (THD), and flicker behave when dimming. In Section 7, the most common analog, digital, and wireless protocols are described, including 1–10 V and DALI. Section 7 discusses the linear, power, and logarithmic dimming curves, as well as the concepts of constant current and PWM dimming. Section 7 introduces the LED driver investigation, where 30 drivers are tested in an automated test setup, and Section 7 presents and discusses the measurement results.

Dimming protocols

For LEDs, the ability to lower the light output intensity is achieved by the LED driver. The LED driver must feature a dimming protocol that translates a dimming input to a specific output current. The dimming input may be supplied by dedicated wires to the driver or wirelessly, depending on the specific LED driver and its application.

In some cases, the maximum current of the LED driver is settable using, e.g., a dip switch contact or a specific resistance value across a dedicated pair of terminals. In other cases, the maximum current can be programmed through a wired or wireless digital interface. When the maximum current is set, the dimming will happen from that current level.

1-10 V dimming

1–10 V dimming is a simple and very popular analog dimming method. The original description can be found in the international standard IEC 60929 Appendix E. The LED driver itself will generate 10 V on the dimming terminals from an internal current source, and the user must reduce the voltage by sinking an adequate current to achieve a lower voltage level and thereby lower dimming input. When the dimming input is 10 V, the driver shall deliver 100% output current. When the dimming input is 1 V or below, according to IEC 60929, the LED driver should deliver its minimum output current. However, some 1–10 V drivers will continue to dim all the way down from 1 V to 0 V, and some even turn off the output when at 0 V. Typically, there is a linear dependency between dimming input voltage and output current, but it is also possible to find drivers with a non-linear characteristic.

There also exists 0–10 V dimming. Here the voltage is sourced by the control unit, and the driver is dimming all the way down to 0 V. In Europe, 0–10 V dimming is not that common, but it is in more widespread use in the US.

Phase cut dimming

Phase cut dimming (commonly known as triac dimming) is a component often found in older and residential lighting installations. Here the dimming is done by cutting the mains input 50 Hz sinusoidal voltage at various angles of the full period. This limits the input current which in turns reduces the output current. There are two types of phase cut dimming: leading edge and trailing edge, indicating from which direction the mains sine voltage is cut.

Phase cut dimming is typically open loop, meaning that there is no feedback mechanism to ensure an accurate output when dimming. Furthermore, it is far from all LED drivers that support phase cut dimming. Using phase cut dimming with an incompatible LED driver will lead to undesired performance and probably flicker. Additionally, using a leading edge dimmer on a trailing edge driver will most likely also not work as intended, and vice versa. However, those LED drivers that support phase cut dimming may be used for retrofit and residential lighting installations.

DALI

Digital Addressable Lighting Interface (DALI) is an international standard for digital control of LED drivers, among others. DALI is developed by Digital Illumination Interface Alliance (DiiA), who is responsible for updates and certifications [3]. A DALI LED driver must pass an official certification test to be allowed to carry the DALI logo.

To use DALI, a dedicated DALI router and a DALI power bus are required, and up to 64 drivers can be powered per DALI bus. For dimming, DALI features 254 different setpoints including OFF for no output. By default, there is a logarithmic relation between dimming input and output current, where, ideally, the output current from one setpoint to its neighboring setpoint increases/decreases by around 2%. Besides basic dimming, DALI enables more complex dimming schemes by defining groups of luminaires, and also defining specific scenes for these groups and/or individual luminaires. Furthermore, other equipment, such as sensors and push buttons, can be installed on the DALI bus, enabling more intelligent lighting solutions. Lastly, DALI can be used to query specific driver and/or LED failures, and the LED driver responds using the same DALI bus. This enables ease of system tests, maintenance, and fault handling.

DALI, like 1–10 V dimming, originates from appendix E of IEC 60929. However, since 2009, DALI is developed and maintained by its own standard IEC 62386, where currently the second edition, commonly known as DALI-2, is being deployed.

DMX-512

DMX-512 is another digital dimming method, which primarily is used in the theater and music stage industries. It also is expanding into architectural lighting solutions and other areas where fast and accurate lighting control is required. In general, DMX-512 is a one-way communication line from controller to driver, but it can be expanded with remote device management (RDM) to enable two-way communication functionality. For DMX-512, a total of 256 dimming levels can be set, but extensions to the protocol exists that allow a higher number of dimming levels if required.

Dimming via wireless

As an alternative to the wired dimming methods, several wireless methods exists. Especially Bluetooth (BLE), WIFI, and Zigbee are most commonly used, where the main benefit is the possibility to wirelessly control the light output, e.g., using smartphones and tablets. Most smartphones and tablets support WIFI and BLE, whereas Zigbee requires a dedicated gateway router connected to, e.g., a WIFI home network.

The typical range for WIFI is 45 m, for Zigbee it is 10 m, and for BLE it is 100 m in clear line of sight [4]. Furthermore, Zigbee and the newest BLE v5.0 support mesh networks for increased range, i.e. luminaire to luminaire communication without additional hubs or routers, whereas WIFI needs additional access points to increase its range.

Summary of dimming protocols

Having discussed the most used and popular dimming methods, Table 1 summarizes each of the protocols and their connectivity.

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Table 1: Summary of dimming protocols, their connectivity, and number of individual addresses.

Protocol	Connectivity	Individual addresses
1–10 V	Analog	1
Phase cut	Analog	1
DALI	Digital	64 per bus
DMX512	Digital	512 per universe
Zigbee	Wireless	65000
BLE	Wireless	32000
WIFI	Wireless	250

Dimming characteristics

Dimming of luminaire light intensity is the LED driver's translation of a dimming input to an output current. However, the relation between the dimming input and the output current is not required to linear.

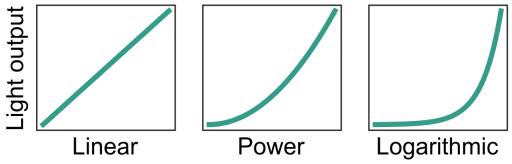

Figure 2: Examples of various input dimming characteristics, and how the dimming input is translated to light output.

Three common dimming characteristics are shown in Figure 2. For 1–10 V dimming, the light output is often linear with the dimming input, typically with an offset of 1 V. For DALI, the default relationship between light output and dimming input is logarithmic to account for the non-linear perception of light intensity of the human eye. In some cases, there is a quadratic (or, generally, a power) relationship between dimming input and light output.

Constant current and PWM dimming

Regardless of dimming protocol, there are basically two different ways to dim a LED: constant current — also known as amplitude modulation (AM) — or pulse width modulated (PWM) dimming.

For PWM dimming, as depicted in Figure 3, the output current alternates between 100% and 0% at a high frequency — typically around 200 Hz to 400 Hz. The duty cycle of the PWM is therefore directly proportional to the average output current.

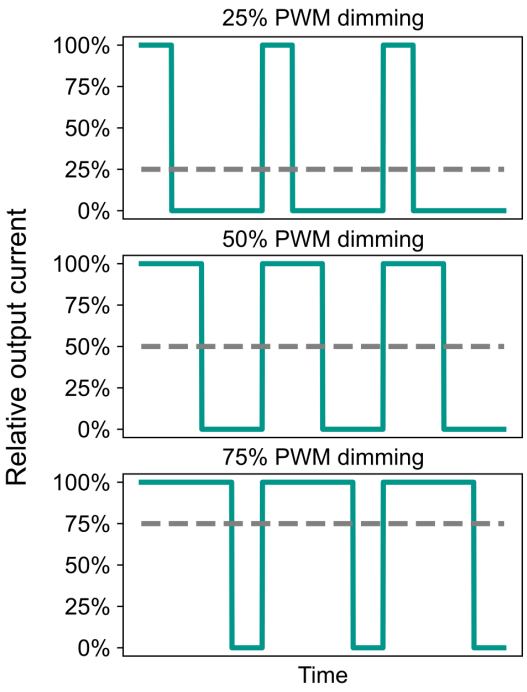

Figure 3: Concept illustration of pulse width modulated (PWM) dimming, where the output current is either at 100% or 0%. The duty cycle of the PWM is proportional to the average of the output current. When the frequency of the PWM is high enough, light output is consider constant for the user.

The main benefit of PWM dimming is that the output current when ON is at 100%, and the LED is operated at its most preferable operating point, ensuring a constant color temperature when dimming. The main drawbacks are 1) concerns whether 200–400 Hz flicker is unhealthy for humans (as discussed further in Section 7) and 2) a significant reduction in LED efficacy.

For constant current, the LEDs are dimmed by reducing the amplitude (mean or DC value) of the output current. The main benefit is a virtually flicker-free output current, which is considered of higher light quality. The main drawback is that the color temperature, especially of older generation LEDs, may change with current amplitude.

Introduction to LED driver investigation

This section introduces the LED driver investigation method and measurement setup.

The LED drivers are selected to operate within the following selection criteria:

- Rated output power: 20–70 W
- Maximum output voltage: 60 V
- EU mains
- Current controlled
- DALI or 1–10 V

A total of 30 LED drivers are used in the investigation.

It should be noted that effort has been put into selecting drivers from different manufacturers to capture as many dimming behaviors and performances as possible. That being said, the vast number of drivers available on the market makes it impossible to fully cover the entire LED driver landscape.

Automated LED driver test setup

An automated test setup is implemented for the dimming behavior investigation. The purpose of the automated test setup is to ensure a consistent test environment for all devices under test (DUT).

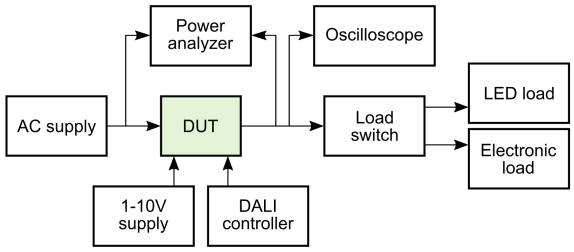

Figure 4: Overview diagram of the automated LED driver test setup. The setup ensures that all devices under test (DUT) are tested under identical conditions.

The overview of the automated test setup is shown in Figure 4. An AC supply is used for the input, and a programmable load array used for the output. The loads in the load array are both various LED loads as well as an electronic load, which enables characterization at rated load for each driver. A power analyzer is used to measure mains-related performance metrics such as efficiency, power factor, and THD. The control is a either a 1–10 V source or a DALI controller, dependent on the control input of the DUT. An oscilloscope measures the output current to the load for flicker measurements. All equipment is interfaced by a custom computer program scripted in the Python programming language.

Measurement results of LED driver investigation

This section presents and discusses the measurement results of the 30 LED drivers in the investigation. The purpose is to identify similarities and differences between drivers, and to investigate output current, efficiency, power factor, THD, and flicker when dimming.

Dimming characteristics

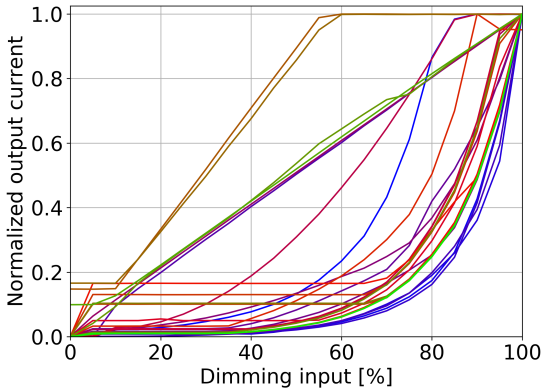

Figure 5: Measured dimming characteristics of the LED driver investigation. Both linear, power, and logarithmic dimming characteristics are observed.

Figure 5 shows the dimming characteristics of the 30 drivers considered in the investigation. The output current of each driver is normalized to its maximum output current, and plotted as a function of dimming input in percentage: for 1–10 V, 100% equals 10 V, and for DALI, 100% equals 254 binary.

As seen in Figure 5, there are four 1–10 V drivers with a linear dimming characteristic from 0–1% to 100%. But there are two 1–10 V drivers that reach the maximum output current already at 60% dimming input. There is one 1–10 V driver with a power characteristic (most likely quadratic), and the rest (mostly DALI drivers) exhibit the logarithmic behavior. For two of the logarithmic drivers, the maximum current is reached at around 90% dimming input. Regarding the lower dimming inputs, there are quite a number of the logarithmic drivers reach their minimum output current at dimming inputs as high as 70%. This can be seen from the plateau at low dimming inputs. Furthermore, some drivers provide zero output for zero input, whereas others remain at a minimum output current level also at 0% dimming input.

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In conclusion, it seems not feasible to be fully aware of a driver's dimming characteristic simply based on the control method (1–10 V or DALI). The manufacturer data sheet will in most cases provide additional information about the dimming characteristics. But in some cases, the dimming characteristic is not clearly described in the data sheet, and only a live test as done here can reveal the actual behavior.

Efficiency and energy savings

One common pit fall is to assume a constant efficiency of the driver when dimming. In a simple use case, the dimming input is 50% for 50% of the time. Assuming constant efficiency, this should give a total energy saving of 25%. However, typically, the efficiency drops around 5%-point when dimmed to 50%, and the total energy savings are only 19% instead of 25%. Additionally, the driver is often over-dimensioned for the luminaire, for instance already dimmed to 50% when the luminaire is giving full output and 25% in the dimmed scenario. In this case the efficiency will typically drop 10%-points in the dimmed scenario, and this will reduce the total energy savings to only 12.5% instead of the original 25%.

The above simplified calculations are based on constant current dimming. If PWM modulation is used, this will have an even greater impact, as the efficacy of the LEDs change with the current level.

In the manufacturer data sheet, the efficiency is often specified at the maximum output power condition, as the efficiency typically is highest at that point. It provides a means for comparison of drivers, but does not tell the full story of efficiency when dimming is considered. For that reason, most data sheets provide a plot of efficiency over output current (or power).

Figure 6 shows the measured efficiency over normalized output current (i.e. where the output current is normalized to the maximum current of each specific driver). As can be seen, the maximum efficiency varies from around 81% to 93%. At lower dimming inputs, the efficiency drops with output current: at a normalized output current of 0.5, the efficiency for most drivers has dropped around 5%-points from its maximum efficiency; at a normalized output current of 0.1, the drop in efficiency is much more profound, dropping from 8%-points to around 40%-points compared to the maximum efficiency of the respective driver. Therefore, for low dimming inputs, the LED driver efficiency may be very poor, and a significant part of the energy savings potential may be compromised.

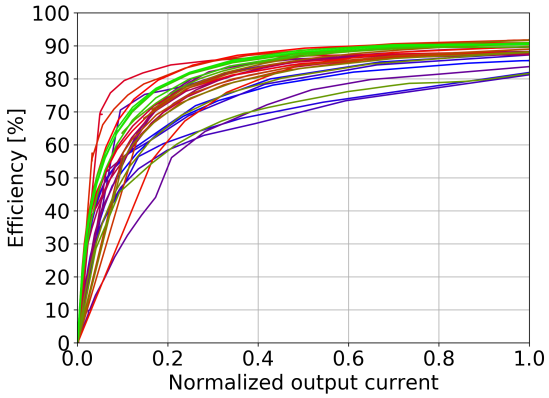

Figure 6: Measured efficiency over normalized output current for the 30 drivers in the investigation.

Power factor and THD

For LED drivers, there are certain requirements for mains-related metrics such as power factor, total harmonic distortion (THD), and harmonic limits. The safety standard IEC 61000-3-2 is part of the CE requirements, and it specifies the input current limits of up to the 40th harmonic of the mains frequency w.r.t. the input current fundamental at rated input power. This directly translates to a maximum allowable THD. Additionally, the limit of the third harmonic is determined based on the power factor. Out of the 30 LED drivers considered in the investigation, all pass the input current harmonic requirements in the IEC 61000-3-2 standard.

In most cases, once the harmonic limits are met, the THD and power factor are at acceptable levels. Still, some LED driver manufacturers put additional self-imposed requirements on THD and power factor, as those might be additional metrics to differentiate against competitor's drivers. Figures 7 and 8 show how the power factor and THD are affected when dimming, respectively. Since LED drivers often are operated below their rated outputs to match a certain luminaire design, knowing the power factor and THD when dimming is of high importance, as the luminaire needs to be safety tested at the reduced output.

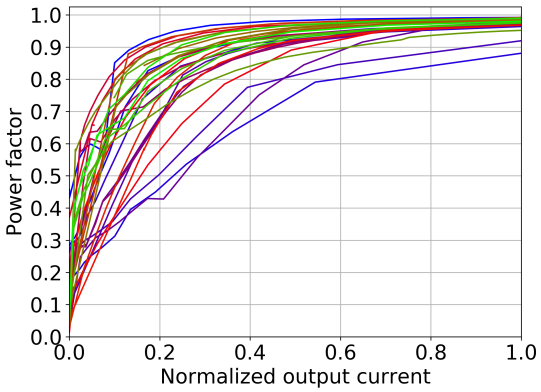

Figure 7: Power factor as a function of normalized output current of the 30 LED drivers in the investigation.

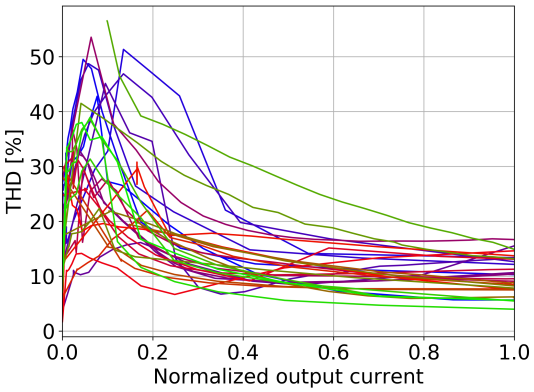

Figure 8: THD as a function of normalized output current of the 30 LED drivers in the investigation.

Flicker

The most basic flicker metric is to divide the peak with the average of the output current and thereby obtain a single value for the flicker, typically at full load. This value is often found in data sheets, but with non-standardized loading conditions, thereby making it difficult to compare. Also, this simple method excludes flicker when dimming, for instance the 100% flicker present when using PWM dimming.

The IEEE1789 standard aims to address the flicker from a human health perspective, and includes flicker when dimming and across a broad frequency range. The flicker is compared to both the acceptable limit and the no observable effect limit (NOEL) over dimming inputs. Note that the IEEE1789 is a recommended practice only and not a safety requirement. An example of a LED driver that passes the IEEE1789 flicker requirements can be seen in Figure 9.

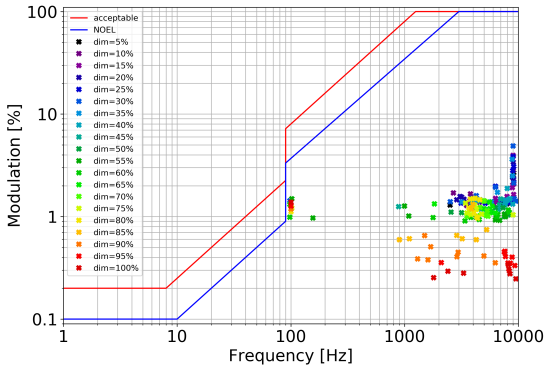

Figure 9: Example of flicker measurement according to the IEEE1789 standard. A total of 10 flicker points (modulation in %) per dimming input is plotted. This driver passes the acceptable and the NOEL lines for all frequencies, and is therefore considered flicker-free.

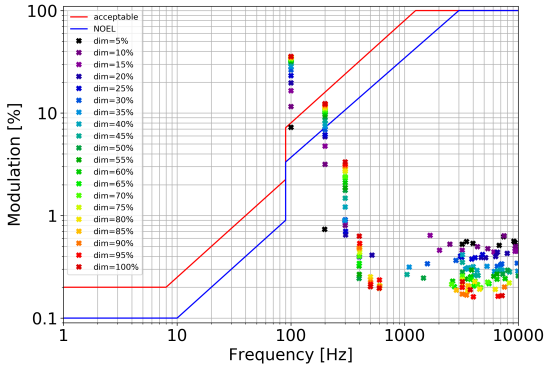

Figure 10: Example LED driver flicker measurement with a significant 100 Hz ripple component and its harmonics. The 100 Hz stems from the rectification of the 50 Hz mains input.

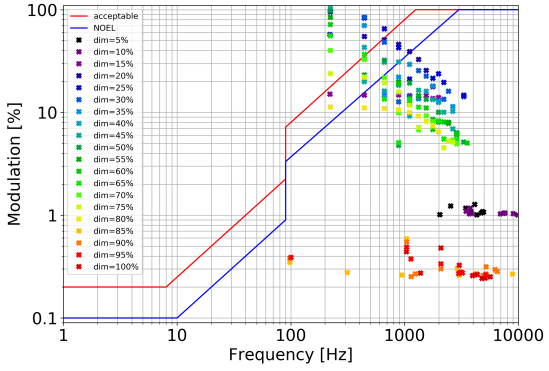

Figure 11: Example LED driver flicker measurement with PWM modulation at around 220 Hz and its harmonics. Note that the flicker is below limits for high dimming inputs as the output current due to output filtering is close to constant at high dimming inputs.

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However, it is by no means all drivers that pass the IEEE1789 flicker requirements. As shown in Figure 10, the 100 Hz ripple, stemming from the rectified 50 Hz mains frequency, is not sufficiently filtered. Or as shown in Figure 11, PWM modulation can be observed resulting in 100% flicker at around 220 Hz when dimming.

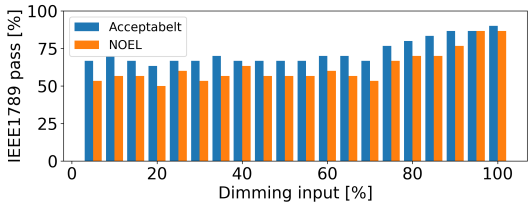

Figure 12: Percentage of drivers that pass the IEEE1789 acceptable and NOEL requirements of the total 30 LED drivers considered in the investigation.

The percentage of the 30 drivers that passes the IEEE1789 requirements for various dimming inputs is shown in Figure 12. For high dimming inputs, more than 75% of the drivers pass the IEEE1789 requirements, whereas for dimming inputs below 75%, around two-thirds pass the acceptable limits and around half pass the NOEL limits.

The IEEE1789 flicker standard used above has gained widespread use. But it also has its critics, and new flicker standards are under development. Especially two new flicker metrics are gaining in popularity: the P_{st}^{LM} metric, which is a measure of visible flicker caused by light modulation up to 80 Hz, and the stroboscopic visibility measure (SVM), which assess stroboscopic effects from 80 Hz to 2000 Hz [5]. The treatment and discussion of these metrics are beyond the scope of this paper.

Conclusion

With LEDs having achieved a high efficacy, the next major leap in energy savings is expected to origin with the intelligent and smart control of luminaires in controllable light systems. The LED driver and the dimming protocols are the main enablers for taking that leap.

This paper presents an automated test setup for LED drivers that enables the characterization and comparison of the dimming behaviors of LED drivers. The output current, efficiency, power factor, THD, and flicker are measured across dimming for 30 LED drivers with either 1–10 V dimming or DALI control. Based on the measurements, a variety of dimming characteristics are observed, as well as various degrees of degradations in efficiency, power factor, THD, and flicker performance when dimming. Careful characterization and awareness of LED driver performance across dimming range is therefore important for future controllable light systems, including IoT, tunable white, and human-centric lighting.

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The authors would further like to acknowledge Rasmus Overgaard Ploug and Jeppe Friberg for their contributions to the automated measurement setup.

References

[1] Owen Comstock, Kevin Jarzomski. "LED bulb efficiency expected to continue improving as cost declines". Available online: https://www.eia.gov/todayinenergy/detail.php?id=15471

[2] Ásta Logadóttir, Sophie Stoffer, Anne Bay, Eik Lykke Nielsen, Rasmus Overgaard Ploug, Toke Meyer Andersen, "Den lille blå om lysstyring" (in danish), Danish energy research and development program (ELFORSK), in print.

[3] Digital Illumination Interface Alliance (DiiA), homepage online: https://www.digitalilluminationinterface.org

[4] "Smart industrial lighting trends: WIFI, Zigbee, and Bluetooth". Available online: https://grealpha.com/news/smart-industrial-lighting-trends-wi-fi-zigbee-and-bluetooth-le/

[5] "Temporal Light Artefacts — TLA". Zentralverband Elektrotechnik- und Elektronikindustrie (ZVEI). Available online: http://en.licht.de/fileadmin/Publications/ZVEI_Publications/1703_E_ZVEI_Temporal_Light_Artefacts.pdf

Influence of Converter Topology on the System Interactions

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Abstract

Electronic converters are widely used in order to supply a LED module. The electrical interface between both was not standardized for many years. At a first glance this interface appears to be trivial, however a professional matching requires many considerations. Inappropriate combinations can affect the reliability of the luminaire leading to a degradation of the light quality. In partnership with ZHAGA a Module-Driver Interface Special Interest Group, short MD-SIG, was founded.

MD-SIG provides the free download of interface specifications at this location:
`http://md-sig.org/specifications/`

The power interface specification describes which electrical information shall be provided in the data sheets of converters and LED modules, how to interpret this information and practical tests for verification. The aim is to provide the data and a method which allows luminaire manufacturers a simple, but reliable matching. The development of LED follows the main goal to design a light source. Strong focus is put on nonelectrical properties like efficiency, optical properties and cost. MD-SIG avoids putting additional burden in terms of electrical requirements and foresees a wide range in each parameter in order to cover also future LED generations. Deep knowledge about the system interactions is required during the development of the converter. The considerations have to cover basic matching needs, fundamental characteristics of topologies including their operating modes, control theory and system interactions. The specification of MD-SIG is advanced beyond the common focus on a pure DC operating point. During converter design it allows an improved prediction of the following key interactions.

The LED module is part of the output filter:
In many converter topologies the module parameters directly influence the roll-off frequency of the filter. This is especially important for low cost designs which use single stage power converters. In these designs the output filter has to suppress not just the high frequency ripple but also the 100 Hz or 120 Hz modulation caused by the supply from standard AC mains. The resulting current ripple and the modulation of the light are not only depending on the converter, but can change when a luminaire manufacturer changes just the module. A second consequence of the filter transfer function is the resulting modulation of the module voltage. Large voltage modulations have the potential to trigger an overvoltage shut down or voltage limiter even when the average voltage is below the protection threshold.

The LED module is part of the current control loop:
Depending on the converter topology and operating mode, the module parameters influence the loop gain of the control loop by multiple mechanisms. The module parameters can directly raise the loop gain, decrease gain and phase margin hence causing instabilities. This could lead to flicker, stroboscopic effects, flashing or in the worst case even damage the hardware.

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Scope

This paper will highlight a selection of system interactions[1] and topologies.

Interactions in scope:

- Temporal light artefacts (TLA)
- Impact on the current regulation loop
- Feed through of input voltage pertubations

Topologies in scope:

- Single stage PFC converters, i.e., boost or flyback
- Single stage PFC converter followed by linear regulator
- Multistage converter with buck output stage

While the impact on the current regulation loop mainly is of relevance during the design of a converter the temporal light artefacts have gained attention of luminaire manufacturers and end customers during the last five years. Publications of numerous organizations like NEMA [1], ZVEI [2] and CIE [3] are available. IEC is actively working on the international standardization. TLA often are regarded as an effect which depends on the chosen converter only, but in fact the differential resistance of the module and the module voltage can both have a significant influence on the resulting TLA. When a luminaire manufacturer changes to a module with newer LED type, it is possible that the TLA are affected.

Basic matching

The LEDset Power Interface Specification [4] visualizes the matching of module and converter in a voltage vs. current graph.

The possible output operating points of the converter are displayed by an area which is limited by the maximum voltage, minimum voltage, maximum current, minimum current, maximum power and minimum power. With respect to the tolerances and systematic drifts of the module forward voltage the expected operating points of a module will appear as a line, when the module is driven with a constant current. In case the current is changing, the line will widen to an area of expected operating points. In essence all expected operating points of the

[1] The considered system consists of the converter with module.

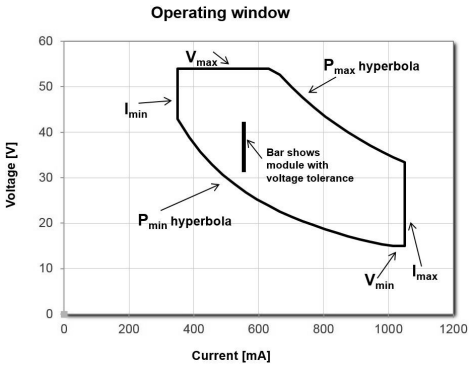

Figure 1: Operating window of OT*i* DALI 35/220-240/1A0 LT2.

module shall be positioned inside the area of possible operating points of the converter. In case some operating points violate the limits of the converter the system may run into defects, blinking effects, or shut down — or in the best case a smooth limiter will regulate the current in a manner which keeps the operating point inside the limits of the converter.

Differential Resistance

Beyond this basic matching the power interface specification of MD-SIG is specifying the differential resistance, which describes the slope of the diode characteristic. The differential resistance is defined as the ratio of a voltage difference divided by the corresponding current difference. Low differential resistances indicate that already a small change of the voltage will cause a large change of the current.

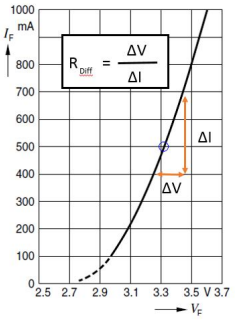

Figure 2: Diode characteristic.

This slope of the diode characteristic has a significant influence on the interactions between module and converter. It interacts with the output filter influencing the frequency response and phase shift. In topologies with an intrinsic voltage source characteristic it influences the loop gain of the current control loop over the entire frequency range starting from DC. In digital implementations

it additionally affects the size of the output current steps.

All these mechanisms have the potential to increase the TLA, influence the smoothness of a dimming sweep or violate the stability of the current control loop, which in the worst case can lead to defects.

Depending on the rated module voltage and rated module current the differential resistance can be expected within a certain range. MD-SIG has defined wide ranges in order to give freedom for the fast evolution of the LED design, while the converter shall be designed to cope with the stated range of expected differential resistances.

Single stage PFC converters

Local and international regulations have established stringent requirements on the input current wave shape of lighting equipment. For power levels above 25 W the IEC61000-3-2 [6] is restricting the allowed harmonic content in a detailed table up to the 39th order. Additionally it became a market standard to ensure a THD of less than 10 percent and a power factor of at least 0.95. In short: The converter shall draw a sinusodial current in phase with the mains voltage, when operated at full power.

Modulation of power

A sinusoidal current drawn in phase with the mains voltage directly leads to a modulated instantaneous power at the line input of the converter [5]. The multiplication of both a sinusoidal voltage and current results in an instantaneous power being modulated with the double mains frequency between zero and twice the average power P.

$$p(t) = U_{pk} * \sin(\omega_{primt}) * I_{pk} * \sin(\omega_{primt})$$

$$\boxed{p(t) = \frac{1}{2} U_{pk} * I_{pk} - \frac{1}{2} U_{pk} * I_{pk} * \cos(2\omega_{primt})}$$

Figure 3: Instantaneous power.

The average power P calculates as:

The modulation does not fit to the goal of an unmodulated output power of the converter.

Half of the time the converter will receive more

$$P = \frac{1}{T}\int_0^T p(t)dt = \frac{1}{T}\int_0^T \left[\frac{1}{2} U_{pk} * I_{pk} - \frac{1}{2} U_{pk} * I_{pk} * \cos(2\omega_{primt})\right] dt$$

$$P = \frac{1}{T}\int_0^T \left[\frac{1}{2} U_{pk} * I_{pk}\right] dt - \frac{1}{T}\int_0^T \left[\frac{1}{2} U_{pk} * I_{pk} * \cos(2\omega_{primt})\right] dt$$

$$\boxed{P = \frac{1}{2} U_{pk} * I_{pk}}$$

Figure 4: Power P.

power than required, the other half it will receive less power than required. Consequently an energy buffer is required, which typically is implemented as an electrolytic capacitor.

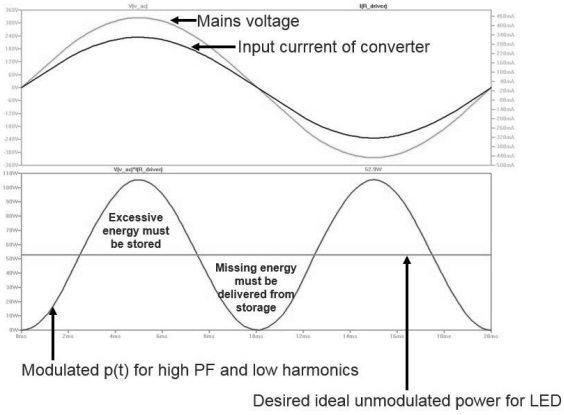

Figure 5: Visualization of power balance.

Energy buffer and filter behavior

Single stage PFC converter topologies like boost or flyback have this storage capacitor placed at the output, electrically in parallel with the LED module. The output stage of the PFC converter can be modeled as a parallel connection of a DC current source, an AC current source and a capacitor. Around a certain operating point the LED module can be modeled as a series connection of a voltage source and a resistor, whereof the voltage source describes the VF at which the current turns almost zero and the resistor describes the differential resistance.

The capacitor and the differential resistance are forming a first order low pass filter. In order to avoid large amounts of AC current in the resistor, the impedance of the capacitor must be low compared to the resistance. Filter capacitor and LED module are sharing the AC current. A lower differential resistance is shifting the AC current towards the module. Module upgrades with more modern LEDs often include a lower differential resistance. Consequently the potential impact on

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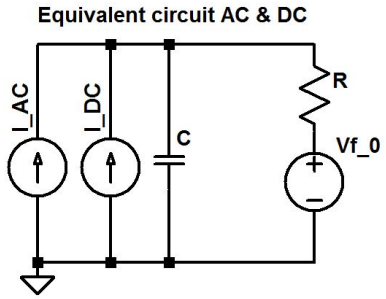

Figure 6: Equivalent circuit of converter output side with LED.

TLA needs to be checked even when the converter is kept unchanged.

In order to calculate the AC current sharing the equivalent AC model is used. DC voltage sources are substituted by a short and DC current sources are substituted by an open.

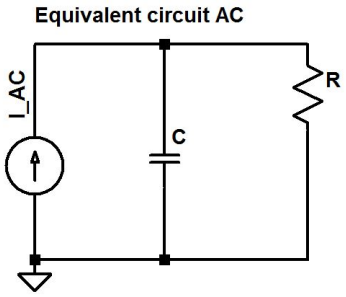

Figure 7: Equivalent AC circuit of converter secondary side with LED.

I) $i_{AC} = i_C + i_R$ II) $\frac{i_C}{i_R} = \frac{R_S}{z_C}$

From I) and II) we get:

$$i_R = \frac{i_{AC}}{1 + j\omega CR_s} * \frac{1 - j\omega CR_s}{1 - j\omega CR_s} = \frac{i_{AC} - j i_{AC}\omega CR_s}{1 + \omega^2 C^2 R_s^2}$$

$$i_R = \frac{i_{AC}}{1 + \omega^2 C^2 R_s^2} - j\frac{i_{AC}\omega CR_s}{1 + \omega^2 C^2 R_s^2}$$

$$i_R = i_{AC}\left(\frac{1}{1 + \omega^2 C^2 R_S^2} - j\frac{\omega CR_S}{1 + \omega^2 C^2 R_S^2}\right)$$

Figure 8: Filter calculation.

Beyond the quality of light also the LED stress needs to be considered, a growing amount of AC results in a higher electrical and thermal load to the LED.

The higher the differential resistance the more voltage modulation will appear. In systems with insufficient voltage headroom the peak voltages may trigger protection circuits of the converter.

Single switching stage followed by linear stage

In order to overcome this fundamental weakness without a huge passive filter a second active power stage is required, however not necessarily a switch mode power conversion. In case the second stage is implemented as a linear power stage the converter often still is categorized as a single stage solution.

The linear regulator can be designed to suppress the modulation almost completely. A full suppression of the modulation requires an average voltage drop across the linear operated power device which equals at least half of the peak-peak AC voltage of the capacitor. During product design a trade off between capacitor size, losses and acceptable modulation must be chosen. In most cases the remaining modulation depth of the current will be adjusted to a specified value below 5 percent. In typical solutions the losses of the linear regulator are reducing the efficiency of the converter by 3%–8%, while the implementation of a second switched mode stage would be expected to reduce the efficiency by 2%–5%.

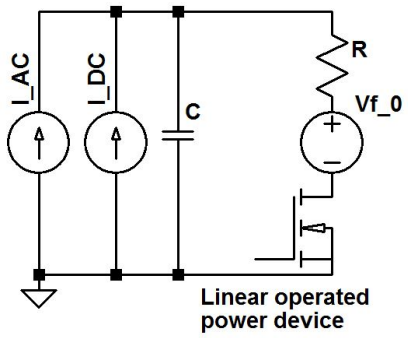

Figure 9: Single switch mode stage with linear regulator.

Multistage converter with buck output stage

In multistage solutions it is a popular choice to implement the output stage as a buck converter operated in continuous conduction mode CCM, because for output voltages ranging from 15 V to 60 V also implementations without synchronous rectification and without complex soft switching

offer high efficiency and moderate EMI performance. In order to achieve a low amount of switching noise the output filter can be realized by a π-filter. Depending on the chosen control method the intrinsic source characteristic will be either a voltage source or a current source. The intrinsic source characteristic describes the behavior of the power stage averaged over one full switching cycle period.

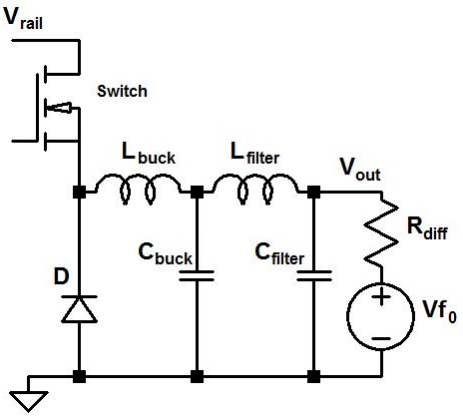

Figure 10: Buck converter with π-filter and module.

The steady state output voltage V_{out} of a buck converter is equal to the averaged voltage of the switching node and can be expressed by the multiplication of the rail voltage V_{rail} and the duty cycle D.

$$V_{out} = V_{rail} * D \quad (1)$$

$$D = \frac{T_{on}}{T_{period}} \quad (2)$$

During the short time of one switching cycle period the rail and the output voltage can be approximated as constant values, consequently the current in the inductor L will show a triangular shape with superimposed DC.

Buck stage with duty cycle control

The control with a certain duty cycle will lead to an output voltage according equation (1). The resulting current in the LED module yields:

$$I_R = \frac{V_{rail} * D - V_0}{R_{diff}} \quad (3)$$

Equation (3) gives some insights about the steady state gain of the power stage including load, when controlled by the duty cycle D. In digital implementations the resolution of the duty cycle is limited and leads to a smallest possible step size for the output current. According to equation (3) this step size becomes a function of the differential resistance. Beyond steady state the gain of the current control loop will also change in its dynamic behavior as a consequence of the interaction with the output filter.

The second aspect of equation (3) is the feed through of modulations from V_{rail} into I_R, which means feed through into the LED current. Especially at high duty cycles, seen at high output voltages, modulations of the rail will cause a strong modulation of the load current.

Buck stage with hysteretic control

Instead of a duty cycle control the buck can be controlled by a hysteretic control of the choke current. The controller turns on the MosFet when the decreasing choke current touches the lower threshold $I_{trsh\ min}$ and turns it off when the maximum threshold $I_{trsh\ max}$ is reached. The current delivered from the switching node to the choke will cycle with triangular shape between $I_{trsh\ min}$ and $I_{trsh\ max}$. The duty cycle is no longer the means of control, but will be a consequence.

In steady state the load current equals the averaged current delivered from the switching node to the choke and can be described as:

$$I_R = I_{L_{buck}} = \frac{I_{trsh\ max} + I_{trsh\ min}}{2} \quad (4)$$

This indicates that the load current would become independent from the rail voltage and independent from the differential resistance. Any real implementation is suffering from delay times of the hysteretic control which does not allow to achieve perfection, but still fortunate performance.

Current control loop

Averaged models of the switching stages by direct implementation of behavioral relationships [7] have been used in order to analyze the current control loop. The analysis follows the proven method using injected signals while operating in closed loop condition [8] [9]. The analysis compares the behavior of the current control loop for a buck converter with duty cycle control versus hysteretic control. The operating point of the LED module was chosen to be 36 V and 1 A. According to MD-SIG the corresponding differential

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resistance can be expected between 1.15 Ω and 10.1 Ω. Both current control loops were designed as PI-regulator. Anticipating an insufficient awareness of the interactions the control loop was designed for a module with a differential resistance of 10.1 Ω. Both models were parametrized to achieve a loop gain of 38 db at 10 Hz and 18 db at 100 Hz for R_{diff} = 10.1 Ω, dominated by the integrating gain at both frequencies. The proportional gain was adjusted in order to compensate up to 90° of the phase shift ensuring a phase margin of at least 70° and a gain margin of at least 15 db.

The examples are not intended to show an optimized solution, but to show the effect of the differential resistance.

The analysis in the frequency domain is based on the bode plot and the Nyquist plot. The analysis in the time domain was based on the transient response.

Current control loop with duty cycle control

The voltage of the switching node was modeled by a voltage source which delivers the averaged voltage of the switching node.

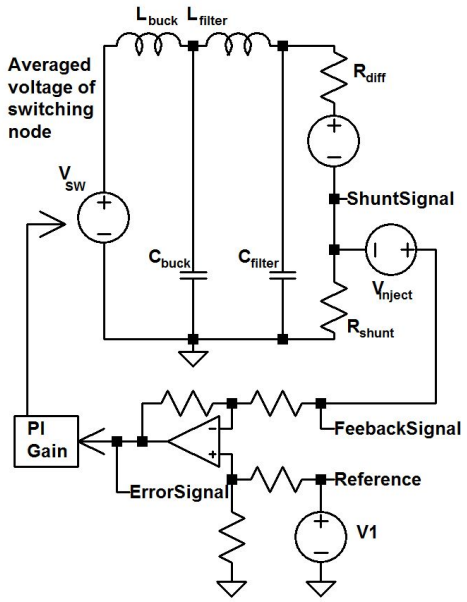

Figure 11: Model of control loop with duty cycle control.

Parameters of the model

R_{shunt}:	1 mΩ
Gain of differential amp:	1000
Proportional term:	$5 * \text{ErrorSignal}(t)$
Integrating term:	$50000 * \int \text{ErrorSignal}(t)dt$
V_{SW} conversion rate:	1 V/V
L_{buck}:	330 µH
L_{filter}:	100 µH
C_{buck}:	4.7 µF
C_{filter}:	4.7 µF

Current control loop with hysteretic control

The current which is delivered from the switching node into the buck choke was modeled by a current source which feeds the averaged current in the buck choke.

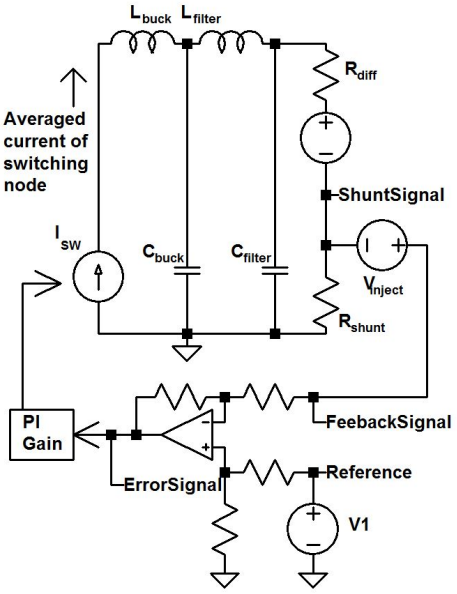

Figure 12: Model of control loop with hysteretic control.

Parameters of the model

R_{shunt}:	1 mΩ
Gain of differential amp:	1000
Proportional term:	$0.1 * \text{ErrorSignal}(t)$
Integrating term:	$5000 * \int \text{ErrorSignal}(t)dt$
I_{SW} conversion rate:	1 A/V
L_{buck}:	330 µH
L_{filter}:	100 µH
C_{buck}:	4.7 µF
C_{filter}:	4.7 µF

Comparison of results

Results of duty cycle control with R_{diff} = 10.1 Ω

The bode plot shows a phase margin of 105° and a gain margin of 15 db. The trajectory in the Nyquist plot does not encircle the point -1+0i. Transient response shows that the load current follows a stepped reference signal with moderate ringing.

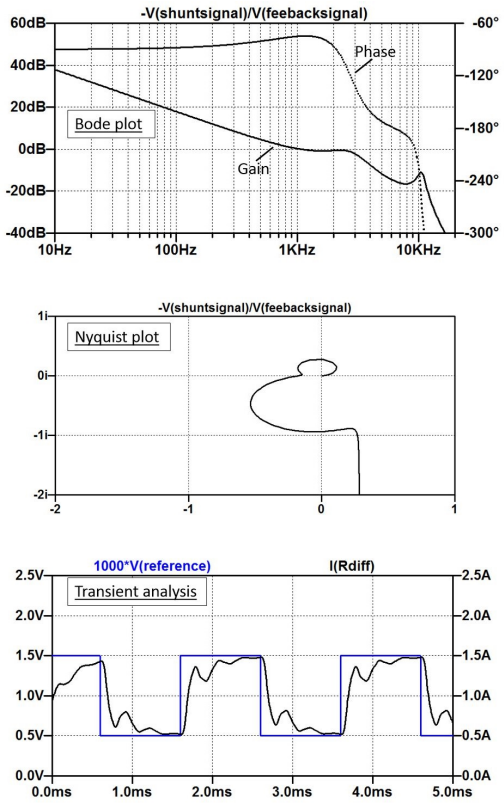

Figure 13: Dutycycle control, differential resistance: 10R1.

Results of duty cycle control with R_{diff} = 1.15 Ω

At the first 0 db crossing of the gain the bode plot shows a phase margin of 60°. But the gain increases again and when the phase shift reaches 180° the system has a loop gain of 2 db. This system will oscillate. This instability also can be seen in the Nyquist plot, the trajectory encircles the point -1+0i. Transient response shows a growing oscillation.

A real converter will typically not reach unlimited values, but oscillate with high magnitude, which does not allow proper control of the light and in worst case could cause damage to the hardware.

Results of hysteretic control with R_{diff} = 10.1 Ω

The bode plot shows a phase margin of 71° and a gain margin of 18 db. The trajectory in the Nyquist plot does not encircle the point -1+0i. The Transient response shows that the load current follows a stepped reference signal in a perfectly dampened manner.

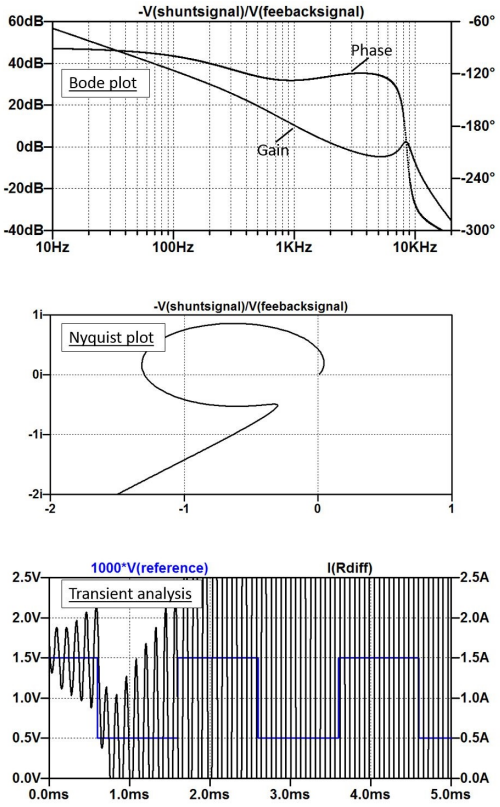

Figure 14: Dutycycle control, differential resistance: 1R15.

Results of hysteretic control with R_{diff} = 1.15 Ω

The bode plot shows a phase margin of 93° and a gain margin of 7 db. The trajectory in the Nyquist plot does not encircle the point -1+0i. Transient response shows that the load current follows a stepped reference signal with moderate ringing.

Conclusions

LED Module and converter are forming an electrical system which needs careful analysis in order to ensure a reliable matching. The popular module specification with rated current and forward voltage is insufficient for the system design. In addition the differential resistance needs to be taken into account in three perspectives:

- Current ripple with corresponding TLA
- Feed through of input voltage pertubations
- Stability of the current control loop

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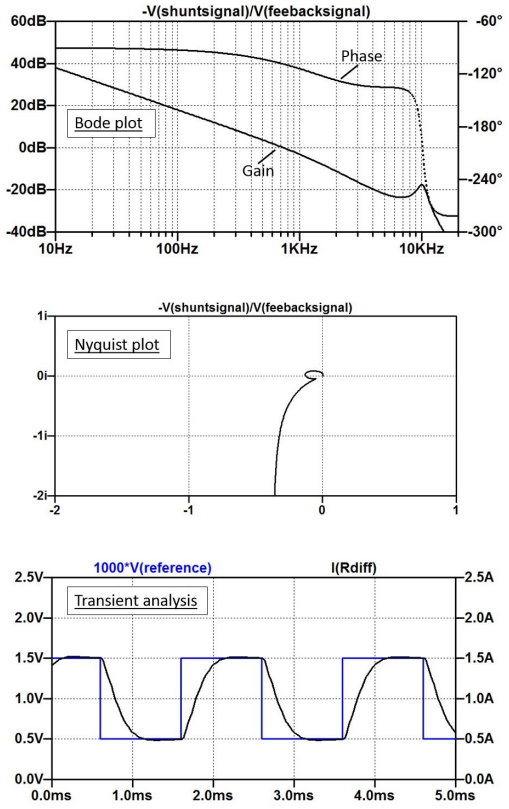

Figure 15: Hysteretic control, differential resistance: 10R1.

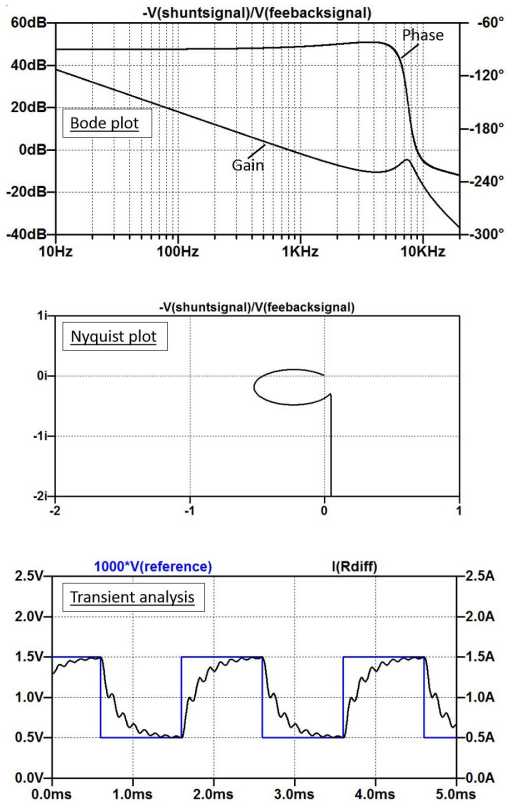

Figure 16: Hysteretic control, differential resistance: 1R15.

TLA and light quality are directly influenced by the differential resistance. Especially when low cost single stage PFC converters are used the system will show a strong modulation of the light with a frequency, which is two times the frequency of the AC mains. The amount of this modulation will depend on the chosen module when the converter remains unchanged. Multistage converters offer the possibility to remove the low frequency TLA.

The feed through of input voltage pertubations is substantial and increases with decreasing differential resistance when a buck converter operated in continuous conduction mode and controlled by the duty cycle is used for the output stage.

A buck converter operated in continuous conduction mode and controlled by a hysteretic current control is preferable in this regard.

The stability of the current control loop is significantly depending on the differential resistance, because of interactions with the output filter.

In topologies with intrinsic voltage source characteristic the differential resistance additionally affects the loop gain over a wide frequency band.

The design of the current control loop needs detail investigation over the full range of expected differential resistances in order to ensure the stability of the regulation loop.

MD-SIG has defined a method how to specify converters and modules including the differential resistance. The expected value ranges of the differential resistances have been chosen wide in order to ensure freedom for LED and module design. The converter has to be capable to operate correctly with any of the expected differential resistances.

References

[1] NEMA Position Paper, Temporal Light Artifacts (Flicker and Stroboscopic Effects), 2015-06-15: https://www.nema.org/news/Pages/NEMA-Lighting-Systems-Division-Publishes-Position-Paper-on-Temporal-Light-Artifacts.aspx

[2] ZVEI Information, Temporal Light Artefacts — TLA: https://www.zvei.org/presse-medien/publikationen/temporal-light-artefacts-tla/

[3] CIE TN 006:2016 “Visual Aspects of Time-Modulated Lighting Systems — Definitions and Measurement Models”

[4] MD-SIG, LEDset Power Interface Specification, Edition 1.2 April, 2017.r

[5] O. Garcia, J. Cobos, R. Prieto, P. Alou, J. Uceda, “Single Phase Power Factor Correction: A Survey”, IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 18, NO. 3, MAY 2003

[6] IEC61000-3-2, 5th Edition, January 1, 2018

[7] Sam Ben-Yaakov, “Average simulation of PWM converters by direct implementation of behavioral relationships.” INT. J. ELECTRONICS, 1994, VOL. 77, NO. 5, 731–746.

[8] Hewlett Packard, “LOOP GAIN MEASUREMENTS WITH THE HP 3577A NETWORK ANALYZER”

[9] Texas Instruments, “AN-1889 How to Measure the Loop Transfer Function of Power Supplies”, SNVA 364A-October 2008 — Revised April 2013

[10] R.D. Middlebrook, Slobodan Cuk, “A GENERAL UNIFIED APPROACH TO MODELLING SWITCHING-CONVERTER POWER STAGES”, 1976, Proceedings of the IEEE Power Electronics Specialists Conference, Cleveland, OH.

[11] Christophe Basso, “The Link Between The Phase Margin And The Converter Transient Response”, http://cbasso.pagesperso-orange.fr/Downloads/Papers/Phase%20margin%20and%20quality%20factor.pdf

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DALI-2: Standardized, Interoperable Components and Smart Luminaires

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Abstract

DALI-2 extends and enhances the strengths of DALI as a dedicated, standardized protocol for digital lighting control. For many years, the lighting community has installed DALI systems that are robust, scalable, cost-effective, reliable and flexible. But now, for the first time, DALI-2 has brought standardization to products such as sensors and other input devices, as well as application controllers, which are the “brains” of a DALI system. Furthermore, with its rigorous testing and verification procedures, the DALI-2 certification program from DiiA brings the promise of significantly-improved interoperability of products from different vendors.

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Introduction

DALI is dedicated and optimized for lighting control, and has many unique features that are not found in other protocols, such as a defined light-output (dimming) curve. The DALI standard includes specific features for emergency lighting, colour control, sensors and controls for lighting, and load shedding, and many more. Other features in development include new functions for control gear; new input devices and features; and the DALI-wireless standard.

DALI is based on robust, bidirectional communication, and enables devices to report failures, answer status queries, and provide other information. DALI commands enable digital control, configuration and querying of devices. Commands can be addressed to an individual device, to groups of devices, or to all devices (broadcast).

Examples of control commands include those that start a fade to a defined light output level, recall scenes or turn the lights off. Configuration commands include, for example, those that change the fade time or change the light level stored in a scene. Examples of query commands include those that ask what the current light output level is, or whether there is a lamp failure.

DALI also provides the flexibility to reconfigure lighting systems using software, without the need for rewiring. Different lighting functions and moods can be achieved in different rooms or areas of a building, and then easily adjusted and optimized.

Development of DALI-2

DALI-2 refers to the latest version of the international DALI standard, IEC 62386. To create DALI-2, the original DALI standard was restructured, upgraded and enhanced with a strong focus on product interoperability. One important feature of DALI-2 is the incorporation of much more detailed and rigorous testing requirements, which are intended to ensure that products from different suppliers are able to work together. As DALI-2 continues to evolve and mature, this will eliminate many of the incompatibility issues that could cause problems with older DALI (version-1) devices in the field.

Alongside the DALI-2 standard, which is published in a number of Parts by IEC, the Digital Illumination Interface Alliance (DiiA) has introduced the DALI-2 certification program. Launched in mid-2017, DALI-2 certification enables suppliers to show that their products meet all the requirements of all relevant Parts of the standard. DALI-2 certified products are able to carry the DALI-2 logo, and are listed in the fully-searchable Product Database on the DiiA website.

DALI-2 certification is enabled by test sequences that are developed by DiiA, and provided to DiiA member companies as a membership benefit. Product test results must be submitted to DiiA, and are then checked and verified before DALI-2 certification is granted. In contrast, DALI version-1 testing relies on self-declaration by suppliers, without any verification checks.

Since the launch of DALI-2 certification, several milestones have been reached. The first DALI-2 products to be certified were LED drivers (control gear) from a number of different companies. These were followed by the first single-master DALI-2 application controllers, and the first DALI-2 bus power supplies (Figure 1).

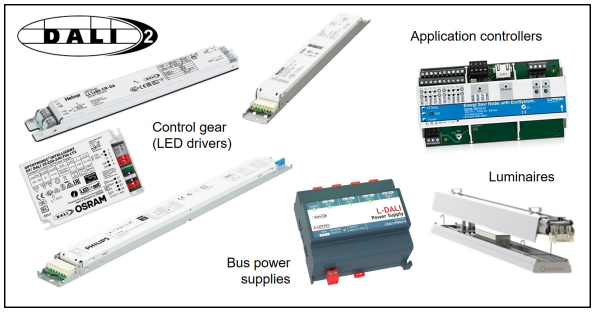

Figure 1: Examples of DALI-2 certified products, which are all listed in the online Product Database on the DiiA website.

Also, the first DALI-2 luminaires were listed on the DiiA website. Currently, DALI-2 luminaires do not have to be certified separately but are required to contain DALI-2 certified components.

At the time of writing, over 175 DALI-2 certified products are listed in the DiiA online Product Database, from a wide range of DiiA member companies. Including DALI version-1 control gear, the database contains more than 1000 products from DiiA member companies. Since June 2018, it is compulsory to list any DALI version-1 products that are available on the market, providing visibility, traceability and reassurance for customers.

New test sequences

Another fundamental improvement in DALI-2 is the standardization of sensors and other input devices, such as sliders, push-buttons and occupancy and light-level sensors, as well as application controllers. With these additions, the DALI-2 standard now extends to all devices in a lighting-control system.

While the relevant Parts of the IEC 62386 standard are already in place for these devices (see Figure 2), DiiA is working hard to develop test sequences that will enable such products to be included in the DALI-2 certification program. The intention is to eliminate cross-vendor incompatibility issues, creating a level playing field and improving customer confidence and choice.

DiiA's current priority is to update the test sequences for Parts 101, 102 and 103. In due course, this will enable DALI-2 certification of multi-master application controllers. At the same time, DiiA is actively developing test sequences for DALI-2 occupancy sensors (Part 303) as well as other input devices. Also on the horizon are test sequences for control gear allowing colour control (Part 209), and for self-contained emergency control gear (Part 202).

The Timeline on the DiiA website (`www.dali2.org/certification/timeline.html`) shows progress in developing all the DALI-2 test sequences.

Further standardization

To create DALI-2 test sequences, DiiA relies on contributions from many of its member companies, who specify, write and review the required documents and software.

At the same time, IEC continues to update existing Parts of IEC 62386 for DALI-2 and to publish new Parts. In recent months, IEC has published a DALI-2 version of Part 207, covering LED drivers (i.e., control gear for LED modules). Among the new publications is Part 221, which covers the control-gear requirements for demand response by way of load shedding.

The DiiA website (`www.dali2.org/dali/standards.html`) maintains an up-to-date list of all the IEC 62386 Parts, as well as the latest version of Figure 2.

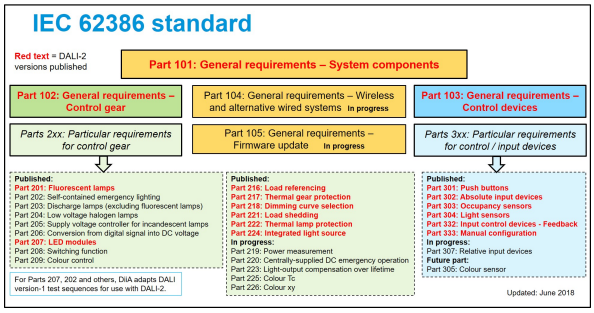

Figure 2: IEC 62386 is published in multiple Parts by IEC.

Recently, DiiA and IEC signed a liaison agreement, enabling DiiA to contribute directly to the development of IEC 62386. The IEC category D liaison allows DiiA to participate in the relevant work group (WG 11 of TC 34) within IEC. Representatives from DiiA now work with lighting experts from different countries who already contribute to WG 11.

Intra-luminaire DALI

DiiA is also actively developing new specifications, and is working with Standards Development Organizations (SDOs) including IEC and ANSI to develop standards based on these DiiA specifications. One example has important applications for smart, connected LED luminaires that can become part of the Internet of Things (IoT). Such luminaires use an internal DALI bus to facilitate the incorporation of sensors and/or wireless communication modules.

As described in a new DiiA specification, the internal LED driver used in this application can provide power to some devices on the DALI bus. Other DiiA specifications define how the LED driver can use a new data model to provide information — such as energy metering and operational diagnostics — in a standardized format that builds on the DALI protocol. This enables reporting of luminaire-specific data, typically via a wireless link, to a centralized server.

An extension of this work is to include a standardized socket that enables sensors or communication devices to be seamlessly connected to the LED luminaire. A modular approach with a standardized interface supports the development of a broad range of such devices, and allows product ecosystems to flourish. Luminaires are future-proofed and can

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be upgraded in line with the ongoing evolution of sensing and connectivity technologies.

DiiA is collaborating with the Zhaga Consortium, which has also developed relevant specifications in this area, to define truly comprehensive specifications as the basis for broad adoption and increased speed to market.

DiiA membership

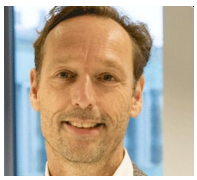
DiiA is an open, global consortium that operates on behalf of its members to stimulate the worldwide adoption of DALI-2 and the proliferation of lighting networks using DALI technology. The organization recently reached the milestone of 150 member companies, including 22 Regular members who contribute directly to DiiA activities including development of test sequences and specifications.

Many companies join as Associate members, while the Community category is open only to luminaire makers, who can use the DALI trademarks (according to DiiA rules) without paying a membership or licensing fee. More information on the benefits of joining DiiA can be found on the DiiA website (`www.digitalilluminationinterface.org/membership/benefits.html`).

Conclusions

With rigorous testing and verification procedures in place, the DALI-2 certification program represents a significant improvement in securing interoperability between DALI products, and is building further confidence in the DALI interface throughout the lighting industry. DiiA is developing new test sequences to bring more product types, including sensors and application controllers, into the DALI-2 certification program. At the same time, IEC is extending IEC 62386, and introducing new standardized functions and features. DiiA is also developing new specifications that will enable new applications such as intra-luminaire DALI, and help smart, connected luminaires to join the IoT.

Connected Lighting Use Cases and End User Benefits: Fixture Based Control for Outdoor and Indoor Lights



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Abstract

As long as the use cases and benefits are difficult to explain to the end user, connected lighting will remain in the dark. Here we describe two distinct use cases for commercial lighting that are based on a digital connection between the LED driver and sensor node. To create mass adoption for these use cases, the digital connection is based on an open standard. This creates competition between driver suppliers and a healthy ecosystem of sensor node providers, benefiting end users.

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Problem to be solved

Connected lighting is defined as a bidirectional connection between the lights and digital operational infrastructure. This means that lighting systems that allow a group of lights to be dimmed by a phase-cut dimmer are not connected because control is one-directional (**to** the lights only) and uses analogue infrastructure. However, controlling a light bulb with a smartphone app is an example of connected lighting because the bulb's status can be reported on digital infrastructure (the phone). The challenge is to find use cases for a bidirectional connection that offer enough benefits for end users over simple and cheap one-directional control of lights. The end user will pay a premium to gain the benefits that such use cases present.

Wired or wireless? We can make a bidirectional connection to a stand alone light fixture in two ways: using wires or wirelessly. Wires are more expensive when bi-directional communication is required – for example, PoE and DALI control are more expensive (to install) than powerline communication or phase cut dimming, which are both single direction). By contrast, wireless transceivers can be cost effective, easy to install, and allow flexible space utilization. From the perspective of adoption speed, wireless is clearly the winner.

In the fixture however[1] the most reliable and cost effective way to create a digital bidirectional bus is to use a pair of two wires between the LED driver and Sensor node. Because we can provide power on the two wires to feed the node, we have designated these new class of LED drivers as **sensor ready** drivers.

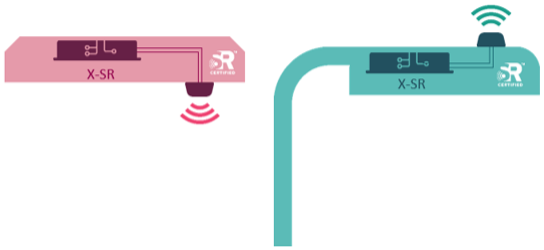

Figure 1: In both indoor and outdoor fixtures, a two-wire interface (TWI) demarcates the sensor-ready driver and sensor node. The TWI provides digital bidirectional communication and power to the node.

[1] Compare USB interface in car or computer: inside the car/computer a wired connection connects the USB interface to the main microprocessor.

A two wire connection in the fixture

Figure 1 shows a schematic diagram for indoor and outdoor applications, showing the bidirectional connection between a sensor ready LED driver and sensor node. In the indoor case, occupancy and daylight sensing are combined with the wireless transceiver. In the outdoor case, the transceiver needs to look to the stars for long range communication to the digital backend infrastructure and is therefore mounted on top of the fixture.

In both cases, the demarcation between sensor node and sensor-ready driver is optimized for choice and flexibility. Costs are minimized by integration of functionality in the driver that usually sits in the control box. This control box would normally power the sensor node, using similar mains electronics already available in the LED driver. Also noise reduction, EMI filtering etc. are anyway available in the sensor-ready driver, making the overall solution more cost effective. Another way to improve cost effectiveness is to use a standardized protocol, reaching scale. DiiA, ANSI, and Zhaga were used to define the Sensor Ready (SR) protocol.

Use case 1: asset management and remote operation

City operation is complex because of the huge variation in assets that need to be maintained. It is a given that all electronic equipment, from the bikes in a bike-sharing program to mains power sub-stations, will eventually break down. And although lighting is much more reliable these days the failure rate is still on the order of 0.1 percent per 1000 h. Replaicing failed LED fixtures is more complex than it appears because cities don't have a standardied installed base and fixture designs vary widely, including LED currents, quantity, and type. As a result, lens plates and LED driver-types vary too. In fact, within a specific LED fixture design, a production batch might be optimized and different from earlier batches as LED suppliers improve their products.

To optimize maintenance, all of this information for hundreds of thousands of city lights needs to be stored in an asset management database. Such databases can now be created automatically with

bi-directional connections allowing city lights to self-identify upon initiation.

Bi-directional operation of the lights is achieved by adding a wireless node on top of each fixture. This allows cities to control the light's output, but also pull up information from the sensor-ready driver to create the asset management database. This functionality requires a digital connection from the node to the driver. The ability to create an asset management database from a bidirectional connection is in many cases a 'free' benefit because the upfront investment of the bidirectional connection can be retrieved from energy saving. In many cases the payback time is shorter than the return on investment in extra power generation facilities. Clearly utilities that own street lights are most favorable target customers for this use case since investing in connected street lights allows them to defer capital investments in new generation facilities.

Use case 1: Expanded benefits

Cities could benefit in other ways too, as connected lighting can now reduce the hurdle for other sensor deployments. By creating a digital biderectional bus inside the fixture, we have established a multimaster situation such that more devices can be added to the street lights. As these devices are added to the street lights their status update can be reported over the sensor node network already created for the remote operation of the city lights. Smart Parking, flood detection, and traffic counting technologies are all examples that have enough peripheral processing to allow use of the same network and access point.

Another benefit for cities is that the clear demarcation we created between lights and network prevents vendor lock-in, freeing cities to change their remote operation provider to reduce costs or gain other commercial advantages. This is such a strong benefit that it's likely to drive manufacture of fixtures with a mechanical low-voltage socket simply to future-proof the lighting equipment.

In fact, this mechanical socket has a use case parallel to the USBs in a computer: USBs open the way for future use cases not managed or orchestrated through the computer industry but from peripheral devices. This makes new business opportunities possible.

Figure 2: A low-voltage socket makes field install and future-proofing feasible.

Use case 2: Measurement and Validation in indoor lighting

Lighting renovation payback times are complex and a lack of clarity about the benefits often prevents indoor lighting customers from switching to a new technology even though it would enable cost savings or better lighting. Also, in new installations, the most cost effective way to illuminate a factory, warehouse, school, or office might not be the cheapest as power consumption, maintenance problems, or even end user dissatisfaction favor other technologies. Incentives, building codes, and recommended practices can provide greater clarity and narrow the choice, but a fundamental uncertainty remains: how will the space be used, over time, and how does this affect the optimal choice and setting of lighting equipment?

This uncertainty makes measurement and validation (M&V) an important use case for indoor lighting, because it provides a precise way to quantify the clear value end users gain from flexibility, automated optimization, and end-user control. With M&V, end users can identify payback from energy saving, and also of their efforts to optimize the automation.

Consider office lighting: rebates from utilities, and in some cases building codes, may steer towards the use of fixture based sensors for occupancy detection and daylight control. Adding end user override from a wireless switch, and task tuning during the initial installation will capture further energy savings. When measured directly at the fixture, savings can be quantified accurately. With this information, facility managers can optimize light settings based on measured energy

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consumptions. If the building's occupancy decreases, or tenants require more light, the effect of these changes is transparent, with the sensor-ready LED driver measuring power consumption and distributing that data to the access point of the wireless nodes so it can be surfaced to end users.

Use case 2: Expanded benefits

Adding wireless nodes to the lighting infrastructure has other benefits. Once they are in place, other low-power sensors can use the enhanced IT infrastructure of the building. Not only can they find a cheap access point, but the lighting fabric can operate these devices to further control building operation. This takes us to use cases beyond the optimization of lighting equipment. For example, consider a detection device used to confirm the status of a window: open or closed. Energy harvesting detectors can send short messages through the lighting fabric, and use the building's lighting infrastructure to optimize flow of air.

Conclusion: Lighting as the linchpin for IoT, SR as starting point

Lighting offers a powerful starting point for digital integration use cases, both outdoor and indoor. For outdoor fixtures, a mechanical low-voltage interface is ideal to automate the formation of an asset management database, and with the network, and biderectional connection inside the fixture, more sensors can be added. Inside the building, the access point and lighting fabric created for M&V enhances the building's IT infrastructure to allow other sensors to operate use cases outside of lighting. Both integration opportunities rely on a standard digital connection between sensor-ready driver and wireless node.

Connected Emergency Lighting — Safety and Security in Controls and Emergency Lighting

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Abstract

The world is starting to take notice of the importance of emergency lighting after a series of unfortunate events. At this point, it is impossible to tell if the emergency lighting is adequate after a time of disaster when the building is a complete loss, whether it is a natural disaster, a case of negligence or even a terrorist attack. As lighting professionals, wouldn't it be good to know that everything within our control was done to fully assist in the evacuations in these buildings? It would be a relief to know the stairwell lights were completely up to code and performed as expected to aid in this time of peril. The traditional rudimentary procedures to test and report emergency lighting diagnostics is manual, burdensome and inefficient, causing us to speculate how the lights functioned or if they were properly tested and maintained. Unfortunately, these archaic and resource consuming codes have caused people to take shortcuts in meeting the codes or completely fabricating the test process altogether.

But no more.

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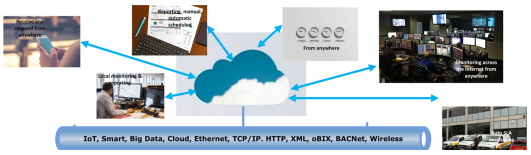

Figure 1: Connecting Emergency Lighting.

Having emergency lighting, only to meet code and just to code, is not enough

No longer is it necessary to take shortcuts such as switching a circuit breaker off or removing a fuse as a shortcut to ensure the emergency drivers are working, or the battery is functioning properly. The days of maintenance or operations personnel walking the facilities and manually pressing a button to ensure the proper function of emergency lighting is already replaced with advanced luminaires containing automatic, self-testing features. IEC.62034 specifies how to do emergency automatic, self-testing, and lighting designers are already demanding this feature in many projects. Now with advanced technology we have the ability to take it a step further. There is now the opportunity, as with many other devices, to become part of a larger, connected IoT ecosystem, providing users with streamlined testing and automatic reporting. More importantly, there is an opportunity to improve functionality in emergency lighting to ensure greater safety and security in the rare times that we need to use the system.

Connecting Emergency Product Starts at The Source

Starting at the emergency luminaire, advanced processing features are necessary to enable monthly and annual automatic, self-testing diagnostic tests and reports, to various specifications. Couple this function with wireless networks, such as Bluetooth Mesh or wired networks, such as DALI or Power over Ethernet (PoE) systems, or even a combination of both, allows you to log those reports in your central database on-site or even in the cloud. Connecting to a network also allows the end user to schedule tests in a time that will not interfere with daily operations and allows you to pull real time diagnostics from the luminaire. Utilizing the right driver will allow you to pull power consumption, temperature readings from the driver and the LED board and various other data. With this data, we can now do predictive analysis and make it possible to predict future failures before they happen, not react to them after they happen.

Sensors Provide Additional Intelligence

Adding another layer of intelligence and functionality could be easily done with the use of sensors. Currently emergency lighting is a ‘dumb’ system, meaning that the luminaire functions normally, unless if the main power is interrupted then it turns on. There is no intelligence to the system. Adding sensors, such as environment, heat and occupancy sensors, and apps changes that. In the event of a fire, with heat and environmental sensors, the location of that fire is easily identified. Additionally, with noise sensors for example, we can pinpoint the exact location of an active shooter (unfortunately in the US and other locations, we must consider such circumstances). Adding occupancy sensors to either of the above examples also allows first responders to know the location of people needing to be evacuated. Further adding intelligence to the data gathered with the sensors allows the system to also reroute people in an evacuation. You don’t want the exit sign to illuminate if it leads you directly into a fire or other catastrophe.

A less catastrophic example would be to utilize motion sensors and machine learning to determine the occupancy of an area where emergency lights are installed. Once a month, the sensors will know when that area is unoccupied, and through machine learning can predict when that space will be unoccupied for long enough of a period of time to run the automatic, self-testing programs. This will limit the manual resources needed and reduce the interruptions caused by a ‘dumb’ system running these programs at critical times of a workday.

Figure 2: Use of Sensors.

Bluetooth mesh Provides a Network to Connect in Hard to Connect Areas

Finally, the technology used could greatly improve the efficiency of an emergency lighting system. Some buildings are simply too large to consider connecting emergency lights together to create any kind of an intelligent system. A wired system could be too expensive to run additional cable to connect, or with a wireless system, the devices could be too far for a robust wireless system to communicate with each other. However, with the new Bluetooth mesh standard, in a fully connected environment, the emergency messages could easily be relayed between devices by utilizing the mesh capabilities. If the lights are Bluetooth enabled, along with the sensors, HVAC, security system, etc., there no longer will be any distance issues.

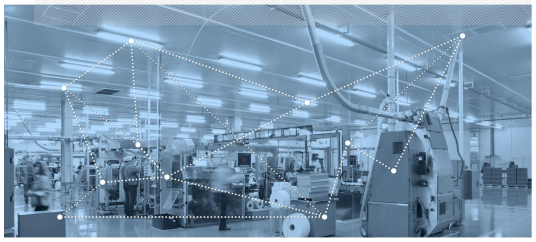

Figure 3: Networks based on Bluetooth Mesh.

Example: Elitedali Converging All Systems in a Building, Including the Emergency Lighting

One example of connecting emergency lighting comes from elitedali. Elitedali is a DALI based lighting control system that uses Tridium's Niagara framework. Niagara is one of the most prevalent platforms used today in Building Management Systems (BMS) and Building Automation Systems (BAS). By integrating the lighting controls, sensors and emergency lighting into the BAS using its native language, you are able to converge multiple pieces of equipment on a single platform and enable them to communicate. The communication, by design, is two-way communication, allowing each device to learn from each other and allowing data to be collected and shared in various ways. The sensors can be used to isolate the location of an event and the system can then direct evacuation accordingly.

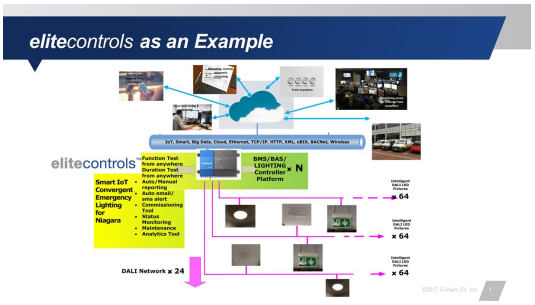

Figure 4: elitecontrols as an example.

Conclusion

Technology today allows us to push outdated processes and technology related to emergency lighting to the wayside. Today's technology allows us to maximize the functionality of emergency lighting and hopefully minimizing loss of life in an emergency. Proper hardware integrated in a luminaire is the first step to intelligent emergency lighting. Including sensors in the emergency ecosystem creates more value and functionality. Finally, connecting the system and creating apps to converge the system into the building creates a true smart building environment where the emergency lights are no longer a hassle or unwanted expense.

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Lighting System Based on Visible Light Communication

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Abstract

This paper presents a lighting system based on visible light communication (VLC). A group of luminaires should be able to communicate through the power LEDs (sender), already present on the luminaire, and an additional photo diode (receiver). The communication has to be cheap and reliable. Objective of the system is the coordination of the luminaires, not the transmission of digital information. The luminaires implement a specific type of swarm behaviour, coordinating themselves through VLC. The authors, members of the Institute for Electronic, Sensors and Actuators ESA of the interstate University of Applied Sciences NTB, developed the system in the context of a project sponsored by the Swiss Innovation Promotion Agency (Innosuisse). The company HSi Elektronik AG (CH-9200 Gossau, Switzerland) was the industrial partner.

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Introduction

In the field of professional lighting and building automation, there is the need for monitoring, control and coordination of groups of luminaires, which illuminate offices, corridors, stairs, garages, etc. Electronic control gears (ECGs), used to power the light sources, offer several international supported wired and wireless interfaces: analogue 1 to 10 V interface, DALI (Digital Addressable Lighting Interface), DMX (Digital Multiplex), KNX (Konnex-Bus), PWM[1] interface, Bluetooth, ZigBee to mention some of the most used. In a first category of systems, the ECGs are connected to a central unit or gateway through a wired or wireless connection and need to be addressed in order to be controlled. The process of addressing the luminaires is time consuming and costly, due to the need of establishing a correspondence between the specific spatial position of the luminaire in the building and its digital address. Other systems use a wired or wireless connection between ECGs but avoid the use of a central unit, achieving a distributed system. Each ECG integrates, in this case, a control unit, and a swarm behaviour can be programmed in the software of the ECGs [1]. Also, in this case, the addressing of the luminaires is necessary, although the process is easier and can be directly performed at the luminaire. In both cases, the luminaires coordinate themselves using presence detectors and photo diodes as input sensors, in order to detect people and moving objects and measure the intensity of ambient light. The integration of the wired or wireless communication includes implementation, installation and approvals costs. In order to overcome these constraints, HSi Elektronik and the Institute ESA discussed the possibility of developing a low cost system using VLC to coordinate the luminaires. A presence detector should be integrated in each luminaire, in order to monitor a specific space area. When a luminaire detects movement of people or objects, it should use VLC to instruct the surrounding luminaires to generate some light themselves. A fading halo should arise around the person or object to be illuminated. In this way, efficient (low power) and effective lighting is achieved for the user. The lighting system should be reliable, not be influenced by ambient light and be possibly ruggedized against disturbances. Such a system would only need luminaires connected to the power grid: no additional costs for wiring or for addressing would be necessary. In addition, such a system could also address the wish for non-proliferation of wireless devices present in certain sectors (e.g., hospitals) [2].

[1] PWM: Pulse Width Modulation

Basic Principle

Each luminaire has three sensors and one actuator (see Figure 1 and 2). The sensors are a PIR[2] presence detector and two photo diodes. The actuator comprises the power LEDs of the luminaire, driven as one body. A microcontroller is the central processing unit of the luminaire. A modulator and a demodulator circuit link respectively the power LED array and the photo diodes to the microcontroller.

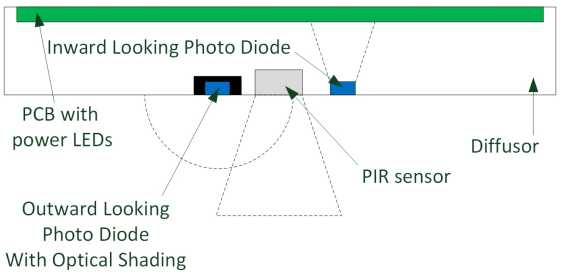

Figure 1: Cross Section of the luminaire.

An optical air path links two different luminaires. The incoming light is the superimposition of several components: a) direct light from another luminaire, through a direct line of sight b) indirect light from another luminaire, through reflections of several kinds c) self-generated light, through reflections of several kinds d) extraneous light generated by other light sources e) ambient light. The PIR sensor of a luminaire monitors a limited spatial area. When it detects moving objects or persons, the luminaire switches on and generates light with a programmed dimming level. Simultaneously the luminaire radiates a VLC command. The surrounding luminaires recognise the command and measure the intensity of the received signal, estimating in this way their own distance to the sending luminaire.

The surrounding luminaires choose a dimming level that decreases with increasing distance. Hence, a fading halo appears around the moving object or person (see Figure 3). In this way, efficient (low power) and effective lighting is achieved for the user. If the PIR sensors detect no more movement, the system fades the light out after a defined time.

The system has to be robust against different

[2] PIR detector: Pyroelectric Infrared detector

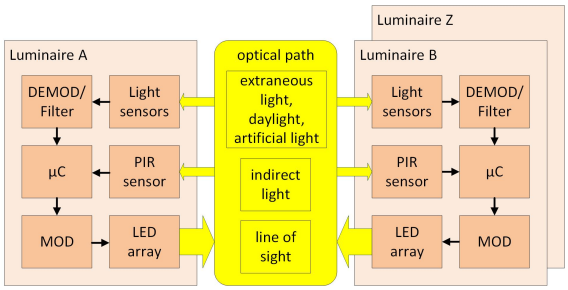

Figure 2: Block diagram of the lighting system.

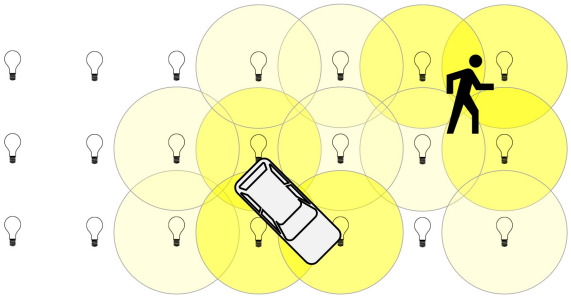

Figure 3: Overview of a field of luminaires.

levels of ambient light, working well during the day and at night. External light sources such as discharge lamps, fluorescent lamps, LED luminaires, even PWM dimmed, should not disturb the system. Additionally, the system has to work in several kinds of ambient, such as offices, stairs and corridors, field paths, garages and be robust against different kinds of surfaces: dark, bright, reflective, opal, shimmering, etc.

Sender

Block diagram

The sender consists of the array of power LEDs, which are primarily the light source of the luminaire. A first power supply, connected to the AC power network, generates a constant output voltage (for example 24 or 48 V DC). A second stage, configured as a step-down converter, regulates the current sourcing the LEDs (see Figure 4). The microcontroller sets the target current of the step-down converter according to the desired dimming level.

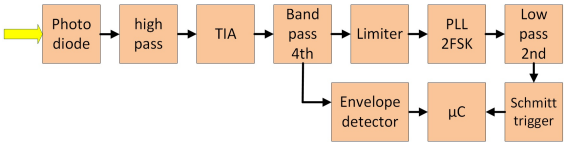

Figure 4: Block diagram of the sender.

During normal operation (lighting), which is also the communication receiving mode, the output current of the step-down converter and its regulation circuit are compelled to have a low bandwidth, in order to achieve very good current regulation and therefore a very stable light emission, so as not to disturb or saturate the sensible receiver circuits. During transmission mode, the output current of the step-down converter and its regulation circuit are compelled to have a wide bandwidth, in order to react rapidly and be able to generate a sharp square wave signal with a frequency in the range of 10 to 11 kHz. A variable filter, controlled by the microcontroller, achieves the change in the bandwidth of the step-down converter. The stable light emission during normal operation allows achieving longer communication distances. The luminaire is able to send messages through a FSK[3] modulation scheme. The sender is able to generate two distinct frequencies to code respectively logic 1 and logic 0 (see Figure 5).

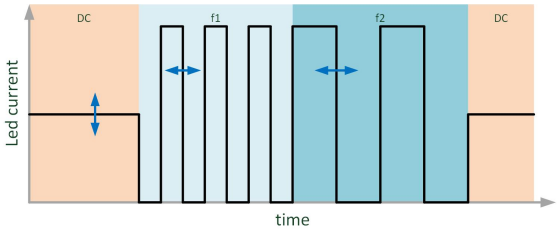

Figure 5: Overview of the communication scheme.

Current control versus PWM

The current control dimming was preferred to PWM dimming, because a cheap 8-bit microcontroller has no high-resolution PWM modules, needed to realize smooth dimming at very low brightness levels and at relatively high PWM frequencies (25 to 50 kHz). Additionally if the frequency of the PWM is not precise, adjacent luminaires can potentially generate disturbing stroboscopic effects [3]. Finally, the use of current control allows the development of an easier and more efficient receiver, which does not have to filter the eventual PWM frequency used in the lighting mode.

Self-calibration of the luminaire

A challenge of the switching between lighting mode with constant current and transmission mode with PWM is to maintain constant brightness, despite dimming level: the observer

[3] FSK: Frequency Shift Keying

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should not perceive any change in luminous intensity. PWM allows a linear regulation of the brightness, through the ratio between on time and the period of the square wave. Current control in contrast allows linear regulation of the current but is affected by the nonlinear relation between current and the luminous flux of the LEDs [4]. The overall tolerances of the components also affects the brightness levels achievable through current control and PWM. First experiments showed that the calculation of the duty cycle of PWM corresponding to a specific current level did not work well enough: brightness steps were still perceivable when the luminaire switched from lighting mode to transmission mode, especially at low brightness levels. In order to solve the problem, an additional photo diode were used, which directly senses only the self-generated LED light (see Figure 1). At startup, the luminaire now generates three short brightness sweeps (25 steps). During the first sweep, brightness is changed through current control. During the second sweep, brightness is changed through duty cycle control of a PWM with constant amplitude, run with the first FSK frequency (10 kHz). The third sweep equals, in principle, the second, but is run with the second FSK frequency (11 kHz). The internal photo diode measures the different 75 brightness levels and generates a calibration look up table. States in between are interpolated. In this way, an effective compensation can be achieved and the switching between lighting mode with constant current and transmission mode with PWM is no longer visible. A continuous fine tuning of the calibration of the brightness levels during the switching between lighting mode and transmission mode could be additionally implemented, although not pursued in this project.

Sending messages

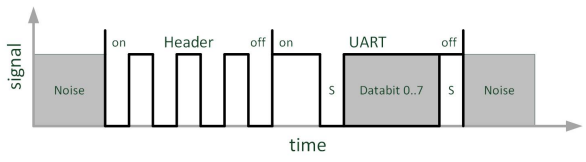

Figure 6: Communication protocol.

When the PIR sensor detects movements, the sender switches to transmission mode and radiates messages, which consist of a synchronisation header and of a command byte (see Figure 6). Three commands are possible: a) movement detected b) broadcast on c) broadcast off. Further details will be explained in section IV dedicated to the receiver and in section V dedicated to swarm behaviour.

Receiver

Block diagram

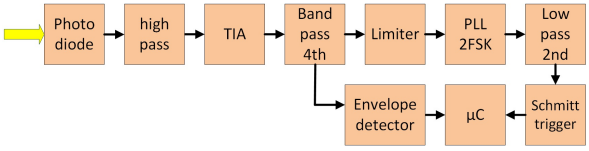

Figure 7: Block diagram of the receiver.

The receiver sensor is an outward-directed photo diode, which is optically shaded from direct self-generated light (see Figure 1 and Figure 7). A first high pass filter decouples the slow changing ambient light, avoids saturation and increases sensitivity of the following stages. A high gain transimpedance amplifier (TIA) converts the photocurrent into a voltage level. A band pass filter then selects the frequency band of the FSK modulation. After an additional amplifier combined with a limiter, the signal feeds a phase locked loop (PLL), which is able to snap in at both frequencies of the FSK modulation [5]. The output of the loop filter of the PLL, which is a voltage directly proportional to the frequency of the detected signal, feeds an additional low pass filter, which in turn feeds through a Schmitt trigger a digital input of the microcontroller. A timer module recognises the header of the message and a UART[4] module reads the command byte coded through the FSK. The filtered signal of the TIA (see Figure 7) also feeds an envelope detector, which estimates the maximum value of the FSK modulation signals. The microcontroller samples this signal through an ADC[5] and achieves in this way a measure of the intensity of the received signal (RSSI[6]). The RSSI is a good measure of the distance of the sending luminaire and can be used as additional parameter to determine how the receiving luminaires should react.

Receiving messages

A timer module of the microcontroller continuously monitors the output signal of the PLL in order to detect the communication header, consisting of three low and high sequences (see Figure 6).

[4] UART: Universal Asynchronous Receiver Transmitter
[5] ADC: Analog to Digital Converter
[6] RSSI: Received Signal Strength Indicator

After the detection of the header, the software switches a UART module on, which decodes the command byte, then saved in the memory. The header helps the PLL synchronizing to the FSK frequencies. The postponed activation of the UART module allows for noise rejection. This procedure is effective and necessary, because the PLLs unfortunately tunes into spurious noise frequencies during idle phases.

SWARM BEHAVIOUR

The luminaire has two pieces of information at disposal in order to establish its own reactions: the received command and the RSSI. According to these two parameters, a swarm behaviour can be defined.

Commands and swarm behaviour

We defined three commands: a) movement detected (MD) b) broadcast on (BO) c) broadcast off (BF). If a luminaire detects movements through its PIR sensor, it switches on, generates light and radiates one MD command. A surrounding luminaire receives the command and measures the RSSI. The receiving luminaire switches on and adjusts its dimming level according to the RSSI. It does not forward any command. In this way, a fading halo is generated around the moving person or object. After a programmable period, if the PIR sensor detects no movement, all luminaires fade out, starting from their actual dimming level. Therefore, the system switches off gently. If the PIR sensor continuously detects movements, it generates signals in specific time intervals. The detecting luminaire then radiates periodical MD commands, which keep the system switched on. MD commands are radiated only once per PIR sensor detection. Proper time constants choice stabilizes the behaviour of the system. We implemented also BO and BF commands, in order to allow the switch-on or switch-off of all luminaires as a group. This can be useful in case of inspection or of cleaning. In this case, the receiving luminaire forwards the BO or BF command, so that all luminaires can be reached. As a result, the microcontroller ignores in this case the RSSI. A user can generate BO and BF commands through the pushing of buttons on the functional models. In the final product, a smartphone or a special torchlight could generate these commands, because buttons on the luminaire would be impossible to reach. Alternative luminaire behaviours could be implemented, although we intended to keep the first system as easy as possible.

Communication conflicts

A conflict could arise, if several luminaires try to radiate messages at the same time. We encountered no special problem in these cases. PIR sensors are focused on independent spatial zones and therefore generate signals at uncorrelated, random times. In the event that two messages really overlap, the PLL circuit matches the stronger signal.

Experimental results

After calculations, simulations and laboratory tests, we developed a first functional model. We produced ten luminaires, in order to test the system.

Ambient light

Figure 8: Example of indoor test of the luminaires.

The AC coupling of the photo diode proved to be very effective. The receiver is able to work properly in all cases: a) darkness (0 Lux) b) ambient light generated by fluorescent lamps (300 to 600 Lux) c) natural daylight combined with light generated by fluorescent lamps (500 to 1000 Lux) d) bright daylight of a light afternoon (2000 Lux). We made no tests in the presence of direct sunlight, because we considered this case of no real practical relevance.

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Figure 9: Example of outdoor test of the luminaires.

Operating distance

The luminaires were tested, in order to measure their capability to communicate at distance. Ten luminaires were distributed over a distance of 30 m. (see Figure 10). The RSSI and the effectiveness of the communication were measured.

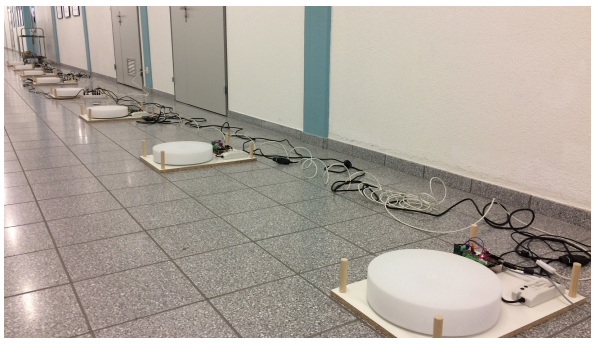

Figure 10: Example of test setup.

We achieved reliable communication at least up to 20 meters, dependent on the characteristics of the environment and on the dimming level (see Figure 11). We have tested the lighting system in the following environments: dark corridors, light corridors, stairwells, outdoor areas with several types of pavement. Communication was stable (10 positive results from 10 tests). Superimposed fluorescent lamps were no problem.

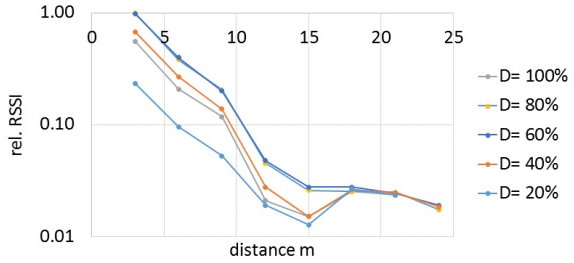

Figure 11: Relative RSSI dependent on distance and dimming level.

Immunity to interference

Although fluorescent and incandescent lamps do not disturb the system, extraneous LED luminaires, possibly dimmed through PWM, could be a potential threat. Therefore, we decided to test the communication in the presence of specifically generated interference. The test setup is depicted in Figure 12: two VLC luminaires are flanked by a third luminaire, programmed to generate light through PWM dimming with 50% duty cycle and a variable frequency, in order to try to disturb the receiver circuits. The distance between luminaires was approx. 3 m.

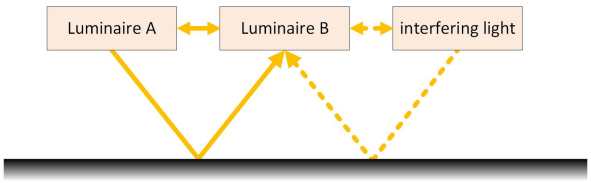

Figure 12: Setup to evaluate immunity to interference.

Figure 13 shows the measurements' results. The error rate is almost negligible for frequencies, which are clearly lower or higher than the two frequencies used by the FSK. When the PWM frequency of the disturbing luminaire nears the band from 10 to 11 kHz (used by the FSK), the communication system can be disturbed. This is the case especially of low or high dimming levels, in which the duty cycle of the communication square pulses is lower than 20% or higher than 80%. Between 20% and 40%, sensitivity to disturbances is still present. In the field between 40% and 80%, the lighting system can function well, despite the extraneous PWM light source.

The presence of interfering light sources is a sensitive issue and has to be taken into account. Although in the case of most applications, such as corridors, garages or staircases, the presence of disturbing luminaires can be excluded by design.

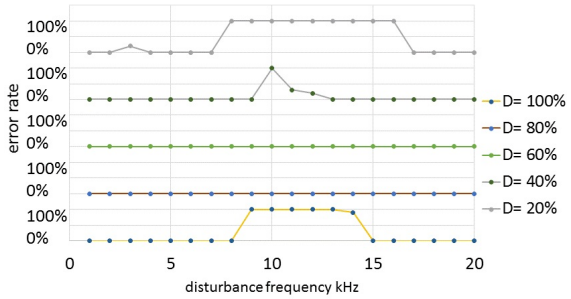

Figure 13: Error rate dependent on disturbing frequency and dimming level.

Strategies to overcome this problem are possible (such as frequency swopping).

Conclusions

A low cost lighting system communicating through VLC was developed, in order to show feasibility. A luminaire, detecting movements in its region, can radiate messages to surrounding luminaires. These in return can receive messages and estimate RSSI. A swarm behaviour can be programmed, without the need to address the luminaires. The system is robust against different environmental conditions and against sources of disturbance. The System works well in the range of 0 to 20 m distance between luminaires. Extraneous LED luminaires or light sources, which are dimmed with PWM, and which use PWM frequencies near to the FSK frequencies of the VLC luminaires, can still disturb the system.

Further development

HSi Elektronik is patenting the solution presented in this paper [6] and is now working on the engineering of the VLC luminaire, developing a product out of the functional models. Further tests and validations are needed, especially connected with real applications. Long-time tests are still pending.

Appendix

Compensation of self-generated light

During the development it became clear, that reflections of the self-generated light are a major obstacle in achieving reliable communication over long distances. We first tried to dim the luminaires through PWM at a higher frequency compared to the FSK frequencies (for example 25 or 50 kHz). Despite the higher frequency, the reflections of the self-generated light were a major disturbance for the receiver circuit. When we changed from PWM to current regulation, we noticed that the inevitable ripple of the current controller also had frequency components in the FSK band and was able to disturb the receiver. Therefore we analyzed methods for the reduction or elimination of the influence of the self-generated light. This measure contribute to the extension of the operating distance of the luminaires.

We evaluated and partially tested the following methods:

- A cheap optical shading is realized around the receiver photo diode (implemented solution in the final design)
- An additional inward oriented photo diode is connected to the input of the transimpedance amplifier (TIA) through a weighted current mirror. The injected current is subtracted from the current of the outward oriented photo diode. Through proper calibration, the compensation of the self-generated light is possible
- An additional array of smaller and switchable inward oriented photo diodes, whose current can be subtracted from the current of the outward oriented photo diode, are connected to the input of the TIA. Through proper switching of the photo diodes array, compensation of the self-generated light can be achieved
- A controllable LCD shutter is placed between an additional inward oriented photo diode and the power LEDs. The inward oriented photo diode is connected to the input of the TIA and its current is subtracted from the current of the outward oriented photo diode. Through calibration of the LCD shutter, compensation of the self-generated light can be achieved

The last method (LCD shutter, see Figure 14) proved to be the best one. It was possible to achieve 28 dB of suppression of the signal generated by self-generated light. Although a small LCD shutter can be bought for only half a dollar, the implementation of this solution was no longer pursued during the project.

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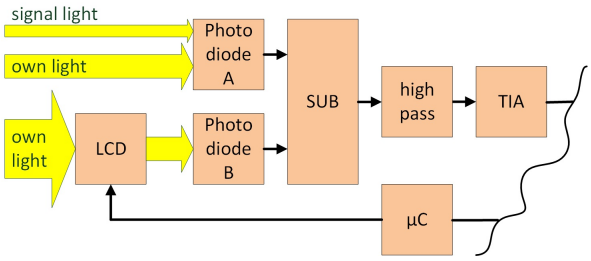

Figure 14: LCD shutter for the compensation of self-generated light.

Acknowledgment

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References

[1] http://www.hsi-astra.ch/technologie/smartlink/

[2] Federal Communications Commission (FCC), Consumer and Governmental Affairs Bureau, *Wireless Devices and Health Concerns*

[3] L. Wang, Y. Tu, L. Liu, M. Perz, I. Vogels, I. Heynderickx, *Stroboscopic Effect of LED Lighting*, Society for Information Display Digest, pp. 754–757, 2015

[4] L. Grodzki, *The Comparison of the Pulse and Constant-current LED Driving*, Przeglad Elektrotechniczny, issue 11, pp. 298–300, 2013

[5] H. Geschwinde, *Einführung in die PLL-Technik*, Vieweg Verlag, 1984

[6] T. Hofer, R. Grabher, *Light and Lighting System*, EP3255817, 2017

Size Matters – Small Form Factors Drivers to Support Flicker-Free Airy and Artistic Luminary Design

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Abstract

As consumers become more sensitive to the quality lighting, a new metric is appearing: flickering. We'll take a look at the flickering of conventional direct AC (driver on board) and DC driver systems for general lighting applications. Besides flickering, size and weight of drivers are increasingly important to support lighting designers achieving slim and light luminary designs. In the past, direct AC drivers could support a light design, but compromised on flickering. DC drivers can help to reduce flickering, but are quite heavy and bulky. With new integrated drivers, the advantages of flicker-free and slim and light drivers can be combined in one products. This may allow designers greater freedom in design, while maintaining a high level of light quality.

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LED Driver Technology Changing

For the last 5 years residential Lighting AC Led architectures have become pervasive in the home. The benefit of AC technology results in smaller and lower cost fixtures. Most of these technologies use a “step driver” which connects the AC to different segments of an Led Array as the AC line Changes. The circuit is very simple, extremely small and low cost Figure 1

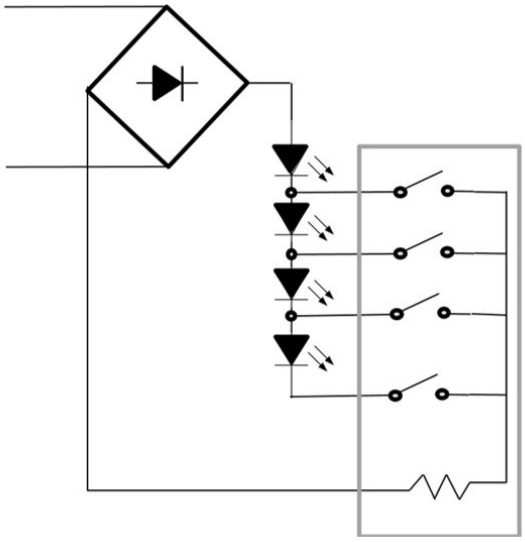

Figure 1: Step driver circuit topology.

The resulting voltage and current waveforms are shown below Figure 2

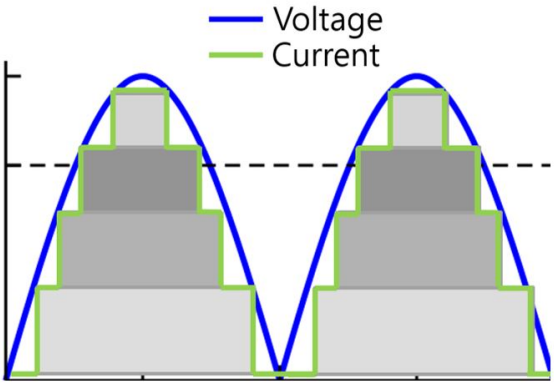

Figure 2: Voltage and Current Waveforms for a step driver.

The luminous flux results in a sinusoidal wave form at twice the line frequency. To most people this is not visible to the human eye but numerous studies have shown this “invisible flicker” can cause fatigue, headaches and in some case seizures. A quick way to see this is to use the camera on most mobile phones which captures the image at a low enough frequency. This shows a significant visible flicker.

There are several legislative initiatives around the world to tackle this problem and California have included limits that have been adopted across the USA.

Low Flicker Solutions for LED lighting

What most people don’t realize is that this will also occur to varying degrees with conventional AC to DC drivers and LEDs. One way to improve this is to increase the output filter size significantly. Recent developments in AC technology have new solutions that have very Low Flicker.

Benefits of AC direct Solutions

There are more benefits to using an AC solution than simply size and cost. Below is an example showing the difference between a down light using a conventional AC to DC Driver and an AC module Figure 3. There are obvious benefits to the fixture size that actually have significant shipping cost benefits. The net size of the packaging is over 25 percent less and the quantity per shipping containers. This resuts in typically over 0.20 Euro shipping cost reduction per unit.

The AC module shown in the Figure 4 fixture has very few parts and not only eliminates the need to ship, handle, wire and mechanically secure the driver but has a 70 percent reduction in the total parts required compared to a DC driver. This has substantial reduction in supply chain and material management. The AC driver parts are very small and are inexpensive to airfreight. Typically DC drivers are bulky, heavy and relatively expensive to ship by air and are normally transported by sea. The net impact of AC solutions can take 5 weeks out of the supply chain.

Size Matters

AC driver technology has historically only been used for AC module light engines. Now AC drivers are available in a more conventional separate mechanical enclosure at a significantly smaller size. There are many Incandescent fixtures that

Figure 3: Size comparison for a same power driver.

Figure 4: Size comparison for a same power driver.

had only wire and a lamp holder. There was no way convert these fixtures to Led because there was no space to fit a driver. New miniature AC drivers are changing this paradigm. Below is comparison of similar power rating AC driver to the older AC-DC drivers. Figure 5. The new AC driver at only 10 mm height can fit in the smallest canopies.Figure 6

Figure 5: Size comparison for a traditional driver versus a Microdriver.

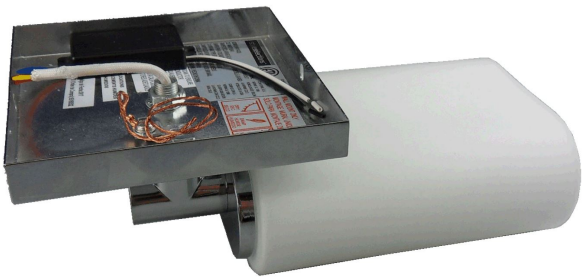

Figure 6: Example of a luminaire with limited space for the driver.

Again in Figure 7 is an example of a traditional "Ice-Hockey puck" style driver compared to a new equivalent AC driver. This new round AC solution is applicable to wall sconce and pendant lights.

Figure 7: Example of a luminaire with Round microdriver integrated.

The small size can completely change the paradigm of the fixture design to enable new and more exotic and elegant industrial design.

Conclusions

AC led architecture has evolved to from a limited low cost and performance solution to high performance and rally dramatically smaller solutions. Many of the draw backs and limitations have changed as the technology has developed. AC led architecture are becoming pervasive mainstream solutions radically impacting light fixture design moving forward.

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Requirements on High Performance LED Driver for Professional LED Lighting

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Abstract

The paper will focus on some key performance attributes of resonant topologies which are currently rising in popularity for modern high performance led driver and explore their contributions to modern energy saving professional led lighting in the mid-power class up to 250 watt.

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Professional lighting solution require high performance LED Driver

Professional LED lighting is overcoming today many shortcomings of the first LED lighting systems. In the early days of LED lighting the focus was predominately on outperforming conventional bulb and tubes in term of power consumption, rather than on light quality.

Since then the request for higher quality lighting has been rising step by step.

Nowadays the features of high quality lighting includes not only deep dimming and flicker free light but also low standby power or full spectrum color control. The combination of these features is adding complexity at large scale to the LED lighting system and the LED driver electronics as well.

Simultaneously regulatory requirements of LED lighting also increased, setting limits for Power Factor or the lately introduced California Title 24 reduced flicker operation definition.

On top of this, the variety of LED modules is exploding, demanding driver with wider window of operations. If this alone wouldn't be challenging enough of course next year's generation LED driver need to be less costly than previous one.

Recent market analysis showed that designs of leading lighting companies respond to these challenges with LED driver based on resonant topologies. Engineers tend to engage into the (more) complex designs of resonant topologies in favor of flyback designs for performance and efficiency reasons. Resonant topologies can be effectively designed from 40 watt upwards to well over 250 watt. There are even higher power designs providing 1000 W or more by resonant topologies. These are often build by separate PFC stage and resonant controller since the industry by and large uses critical conduction mode for the lower power up to 200–300 W and continuous conduction mode for PFC stages greater than 300 Watt driven by the need of efficient but cost effective PFC solutions.

A typical schematic of a resonant topology is split in 3 functional areas:

Marked with blue color are the external components required to set the Power Factor Correction (PFC) and the Total Harmonic Distortion (THD) compensation.

The green colored components are required to set the halfbridge operation, e.g., setting the right working points for the MOSFETS, the power regulation and frequency and the Burst Mode — which enables a very low energy consumption at standby.

The orange components define the working points of the special features of this resonant controller, such as the Brown Out (BO) — which senses the line input voltage directly and protects the MOSFETS in the application in under-voltage events, the Overvoltage Protection (OVP) — which ensure that the output voltage will not exceed critical levels that the designer has defined, the and the over-temperature protection (OTP) which is an in-built temperature protection mechanism, that helps the designer to control hot spots on the PCB and avoid that the LED driver as such will overheat.

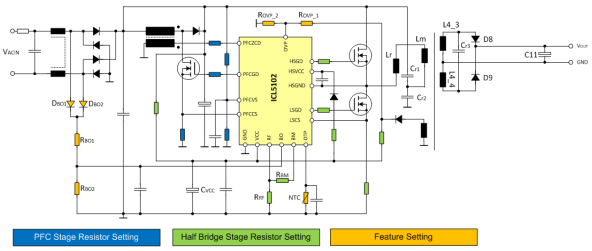

Figure 1: Simplified Resonant Schematic (LCC).

Protections for LED drivers and LED modules

LED driver designers are undertaking significant efforts in protecting their systems against external and internal failure sources to ensure a high level of reliability, long lifetime and a low number of field returns, since field returns are creating cost in order of several times the driver price. Just by looking at the input of the LED driver a lot of challenges can be found. Not only has it to be compliant with the conducted EMI norms but it also has to deal with voltage drops, input voltage flicker, over-voltages and surge events.

In cases of input voltage dips and power failure, a brown out protection eliminates the occurrence of too high and potentially damaging currents within the system, by switching off the LED driver if the input voltage falls below the predefined threshold.

Surge events have to be identified as fast as possible to shut down all active MOSFET to avoid any damage overstressing or destroying the transistors. In order to re-establish proper light output as soon as the AC-mains is recovered, a constant monitoring of the relevant voltages is necessary. This enables high quality designs with short restart time and a low failure rate.

Modern IC controller provides manifold protections supporting the engineering in designing long lifetime LED drivers; this becomes especially important if the unit is designed to work at its limits. A mentionable protection is the multi-level over current protection. The first level is commonly used to limit the power delivered to the output, which might either be a bus or the output capacitor. The second level is triggered during fault conditions and is designed to be able to react timely to very fast occurring magnetic saturation events.

Furthermore operating resonant half bridges, it is essential to have a capacitive mode protection in place preventing a shoot through of the MOSFETs. This failure mode has to be detected as fast as possible and countermeasures like increasing the HB frequency have to be performed to prevent damage.

An open loop protection, as well as an additional primary side over-voltage protection will handle unpredicted behavior of the driver. They are necessary to avoid any damage of the LED modules in events where the driver might get damaged.

As requested by IEC 61347-1:2007/AMD2:2012 the system must be capable of working safely with double the LED load the control gear is actually designed for. This means the driver needs an overpower / overload and a short circuit protection. In many cases this can be achieved through a proper design of the feedback loop steering the correlated IC protecting reaction.

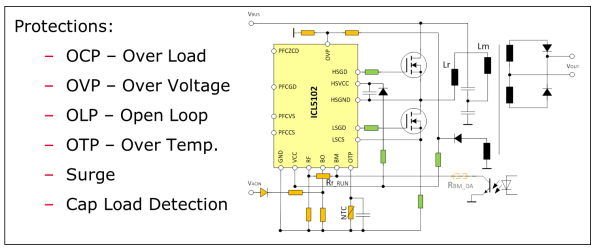

Figure 2: Built in protection in high performance LED controller).

Looking at all the above mentioned design challenges triggered by either external or internal unwanted behavior; it is obvious that a controller IC which is capable of providing all of these protections internally is a huge benefit. It doesn't only save time and design effort but it also reduces the number of components and required PCB space used to implement these functions.

Temperature Control

Decision makers in the early days of LED lighting where often discouraged by the missing reliability of LED lighting systems, by and large caused by driver issues, apart from insufficient thermal designs or missing environmental protection of the LEDs. The build-in protections of modern IC circuits, controlling LED driver, has helped to improve the reliability of the system significantly. The ICs do not only protect themselves, but also avoid overloading key components such as MOSFETS and capacitors and can drive power down in the event of thermal overheating. While most controllers IC have integrated temperature protections, these protections can basically only cover the IC itself. The ICL5102 for example enables designers to connect an external temperature senor (NTC) to sense and monitor critical temperatures at any place inside the LED driver housing, being it near or remote to the controller IC. Designers can tailor the temperature range and sensitivity easily by low cost resistors and decide the threshold for power reduction. The IC comes with inbuilt hysteresis to make sure power is increased only after sufficient cooling.

High Efficiency

High efficiency is required to save energy but also to reduce the thermal dissipation of the driver. Even though LED need to be thermally managed (cooling) most designs prefer to avoid additional cooling effort for the driver electronics for construction and cost reasons.

Apart from aiming to improve the illumination conditions, most important decision factor for adaptation of LED lighting is amortization and cost savings. In popular applications like vertical farming and horticulture lighting, efficiency is among the main decision criterion, since energy cost are key in competing with conventional greenhouse produce, apart from the amount of one-time invest and amortization factors.

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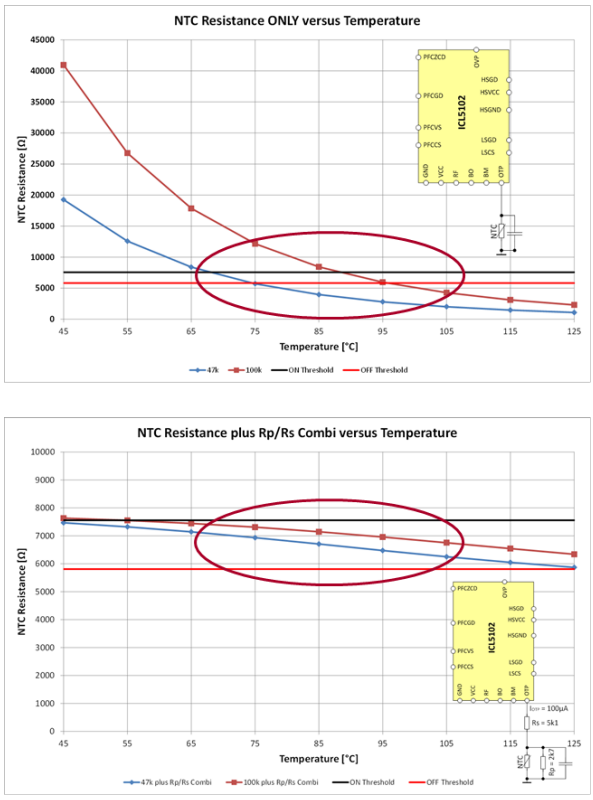

Figure 3: Flexible adjustment of the over-temperature control.

Buyers attracted by cheap purchase pricing only, often underestimate the impact of driver efficiency in relation to purchase cost.

Figure 4 shows a comparison of energy cost over a one year and a five year period at driver efficiencies ranging from 84% to 94%. With only 2% efficiency gain the buyer could accept a 50% higher purchase price!

	1yr	5yrs Lifetime	
Annual operating Hours	8760		
LED Driver Wattage	100		
Price per kWatt/hour	$ 0,08		
LED Driver Purchase Cost	$ 15,00		
			Efficency
Electricity Cost	$ 83,43	$ 417,14	84%
Electricity Cost	$ 77,87	$ 389,33	90%
Electricity Cost	$ 76,17	$ 380,87	92%
Electricity Cost	$ 74,55	$ 372,77	94%
2% efficiency gain equals		$ 8,10	

Figure 4: Cost-effect of LED driver efficiency.

But there is more than one reason to re-consider your purchase budget for LED driver and don't buy (too) cheap: these reasons are called Power Factor and Harmonic Distortion.

While all electronic equipment in the EU connected to public mains must comply with EN 61000-3-2 anyway, there are even very specific requirements detailed for lighting based on power classes, stating the minimum requirement on power factor and harmonics issued. This became necessary with the advent of electronic control gear (ECG), introduced to improve the performance conventional magnetic ballast used for fluorescent tubes. One drawback of these ECG (and essentially also LED driver if they are ill designed) is, that Voltage and Current could become phase shifted, if no properly designed power factor correction (PFC) is in place. This would be resulting in reactive power, drawn from the grid.

Not only communalities but by and large also businesses, office buildings and manufacturing sides are required to pay for reactive power they draw from the grid, therefore savvy buyers will also make sure to postulate stringed requirements in their tender or purchasing specification for both power factor and harmonics.

Today most supplier outperform the requirements to provide a minimum power factor of greater than 0,7 for luminaires or bulbs greater than 8 W and supplier provide typically products with PF of aprox.0,9.

However this is not always the case for the harmonic distortion. The Harmonic Distortion — or short: THD is important to any type of power system, since low THD means higher power factor, lower peak currents, and higher efficiency. But it is especially important to LED driver due to the potentially high volume of lighting units and installed driver in one place, whereas all individual distortion would sum up. The overall issued distortion could infiltrate other equipment or disturb its functions. Hospitals or laboratories with sensitive measurement equipment are among the ones with strong requirements against THD.

With the increasing amount of smart and connected lighting, the focus shifts from PF and THD at full load to the so called light load or low load performance, understanding that controlled lighting systems are often operated at less than full load, providing only the desired amount of light. This operation is a key in the return of invest calculation since every fraction of energy saved by dimming will not only drive the electricity bill down, but also prolong the lifetime of the LEDs as such.

Equipped with (often digital) advanced control algorithm IC's for LED driver can adopt to the load conditions and for, e.g., change from Critical Conduction Mode (which is best suited to provide efficient power conversion at full loads) to Discontinuous Conduction or Wait Cycle Mode.

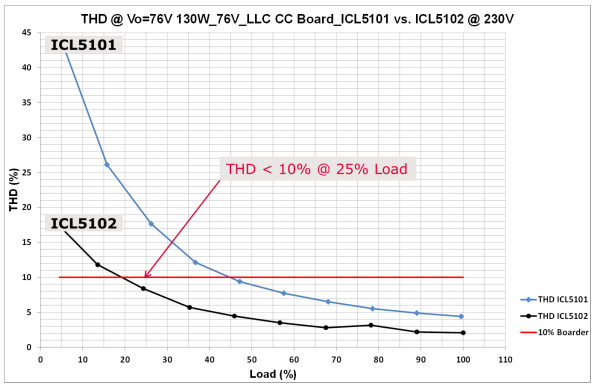

Figure 5: Very low THD of resonant controller, even at low load conditions.

The resulting THD performance over load, measured at 230 V AC in, is shown in Figure 5.

The 2nd curve dubbed ICL5101 shows the performance of previous generation controller, confirming that continuous evolution of the controller family has resulted in significantly better THD performance.

Low Standby Power

A dimmed LED luminaire need to react instantaneously on the dimmer signal and change from "lights-off" to any level of luminosity the user chooses via the control gear. Hence for large time of its life while lights are off, it remains in wait and see = standby mode, this is especially the case with all connected and DALI or 1–10 V controlled devices. LED driver manufacturers aim to offer standby power consumption certainly below 500 mW, while state of the art driver are typically consuming below 300 mW in standby operation. Technically the low power consumption is achieved by an active burst mode operation able to distinguish between 4 different load conditions. In case of low energy demand (standby) the controller enters into self-adapting burst mode, monitoring the energy demand, and only activating power delivery to the output occasionally to just provide enough power to maintain the output voltage and ensure supply for, e.g., for a DALI interface or microcontroller unit or sensor.

Time to light

A human friendly light responds to a tip on the switch without any noticeable delay time. This requirement did become more important in the last years, and companies broadly specifying 200–400 milliseconds as acceptable switch-on times. That does sound like pretty long time in electronics terms where many operations can be performed in µs or nanoseconds. In a typical Led lighting system consisting of a LED module and a LED driver, especially the driver contains many electronic devices. Among them several capacitors as filter or smoothening capacitor, which all need to be charged up at start of the LED driver, which requires time. At the very first moments when LED drivers are switched on also the integrated circuit controlling the switch mode power generation are "booted". And as the following diagram shows this is a rather complex sequence, in order to make sure that LED drivers operation is safe, no power is released until all safety features and protection are up and running, e.g., to avoid LED damaging Voltage overshoots or current spikes.

This chart provides detailed information about the device status from initial start-up (first time power applied) till full operation of the LED driver. The IC enters first of all automatically its internal monitoring mode, to make sure the appropriate Line input voltage levels are reached. Simultaneously the Vcc supply voltage for the IC must have reached a certain threshold. Once these monitoring conditions are fulfilled the device enters the power up and start-up phase.

In this phase the IC is monitoring if the PFC bus voltage and over-temperature and overvoltage levels. If all conditions are well the start-up will be executed and now the device turns on the PFC Gate and the Bus Voltage will rise. The remaining protections such as BrownOut, OVP and OTP are all activated as well, while still the Halfbridge remains turned off.

In the last phase of the very advanced 3-stage soft start, the ICL 5102 will now switch on all Gates, and full power will "flow" through the application and the LED driver will start to deliver power at its output for the first time. Now also all protections are active, e.g., also overpower regulation and overcurrent protection. Especially the device also enables its capacitive load regulation and protection- this specific features prevents capacitive load operation of the

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MOSFETS which could elsewhere lead to destruction of the MOSFETS. While now in full operation the IC is supplied typically from an additional winding on the main transformer. Before that the supply voltage need to be drawn straight out of the grid either via a high ohmic resistor or a startup cell, consisting of a high voltage / low current MOSFET and a simple control circuit. Choosing a resistor over a start-up cell is a decision about performance and cost.

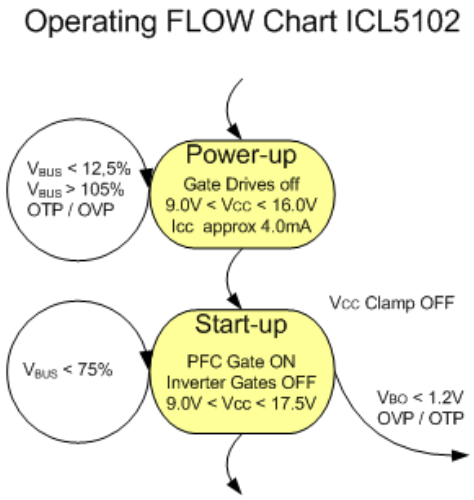

Figure 6: Operating Flow Chart of Resonant Controller.

Cost

In order to achieve a faster start-up of the IC controlling the LED driver, a start-up cell — providing the initial power to the IC, could be added. However is an additional component on the BOM and requiring board space. More elegantly, the IC can be designed to require only very low currents in the range of couple of hundred µA that ca be supplied through a sufficiently high ohmic resistor. After the start-up phase when the IC is self-supplied this resistor just burns energy. This is neglect able when the LED driver runs at full power, e.g., at 40 watt, however represents a major portion when an connected LED driver is put to standby mode while for example waiting for a DALI command consuming only 100–200 mW.

Significant savings can also be achieved by dimension the input filter network, since this is built by rather costly high voltage capacitors and magnetics. If the IC is designed to cause less high frequency noise, this will immediately affect the input filter network, being much leaner than filter required for a “noisy” IC. This cost can often be close to the IC cost boosting the BOM significantly.

Cost of design is usually amortized over the volume of built driver, hence if large volumes of driver are sold they seem at first glance not that significant. The more important factor are scarce resources and short time to market. Resources are more often than not the limiting factors in issuing new LED driver designs. Engineers need to get acquainted with new ICs or new topologies, which both can be time consuming task. In order to support customers in that challenge, Infineon has undertaken major effort in designing upwards compatible resonant controller IC. Customers familiar with ICL5101 can change with 4 simple changes to the latest ICL5102 controller, even re-using the previous PCB for testing purpose, while boosting performance up. With this approach the design times can be reduced to weeks compared to design times of month when starting from scratch. Furthermore reference designs are available and all calculations can be carried out in a guided calculator tool, allowing engineers to alter the design according to their specific needs. With this approach and the long term outlook that successor device ICL5103 will be available with even enhanced features, we have seen an unprecedented interest of the industry in the new resonant controller ICL5102.

Even though many of the topics can be addressed by discrete components, it is easy to witness by taking a look into an open LED driver how crowded the design is and how much efforts designers need to put to manage all parameters meeting the specifications.

Therefore factors like ease of design, build in protections and combo controller with power factor correction helping designers to meet cost targets with design of ever increasing complexity.

The semiconductor industries challenge is to support the LED driver manufacturer with sophisticated semiconductor solution helping to meet the ever increasing specification targets at ever decreasing cost targets. Using a state of the art IC for lighting drivers shortens the time to market, enables platform designs, makes the diver more reliable and saves cost at the same time.

Acknowledgment

Special thanks for support in writing and reviewing this paper belongs to Dr. Michael Weirich and Peter Lenar, both at Infineon Technologies AG.

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Materials & Engineering in Lighting

360 How Next Generation Design Tools Accelerate Time to Market and Secure Design Decisions
by Francois Mirand, Future Lighting Solutions

364 Reinventing Office Lighting — The Making-of an Innovative Office Task Light
by Dipl. Designer Till Armbruester, Licht Kunst Licht AG

370 Injection Moulded Diffraction Gratings on Curved Surfaces. A Breakthrough for a Cost-Effective Industrial Mass-Production
by Dr. Manuel Walch, kdg opticomp GmbH

374 A New Approach to Optical Beam Shaping for Lighting Applications based on Nano-Optics
by Dr. Marek Škereň, IQ Structures s.r.o.

384 Rapid Prototyping of Complex 3D Optical Components
by Dr. Ladislav Kuna, Joanneum Research

390 Semi-Empirical Characterization of Freeform Microlens Arrays
by Dr. Oscar Fernandez (NOMINEE: LED professional Best Scientific Paper Award 2018), CSEM

396 The T-Word: Tolerancing, and its Role in Illumination Optics Design
by David Jacobsen, Lambda Research

402 Multi-Functional Optical Silicone-to-Thermoplastic Over-Molded Component for LED Lighting
by Dr. Francois de Buyl, Dow

408 Flexible Graphite for Superior Thermal Management Solutions in LED Lighting
by Jeff Gough, NeoGraf Solutions LLC

416 Aluminum Oxide PCB - Technology for Developing New Generation LED Solutions
by Dr. Aleksey Osin, RUSALOX

422 Cost-Effective Manufacturing of High-Quality ITO Thin Films on 300 mm CMOS for Next Generation Display Technologies
by Dr. Claudiu Valentin Falub, Evatec

How Next Generation Design Tools Accelerate Time to Market and Secure Design Decisions

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Abstract

The technical intricacies of an LED system design can be astonishingly complicated. Evaluating the many options can be extremely time consuming, and exposes the designer to the risk of making mistaken or misinformed decisions.

LED manufacturers' product selectors or simple parametric simulators can be helpful, but they are not sufficient for full system optimization. Next generation tools will need to be application oriented rather than LED centric, to simulate a system level solution not just the LED components, to support a wide range of options from multiple manufacturers, and to address not only mainstream illumination but also emerging applications such as horticulture and non-visible solid state light sources such as UV LEDs.

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The reason why basic parametric LED selectors were sufficient in the past is because the LED technology was very new and only a few pioneering manufacturers had the products suitable for use in general illumination. After all, the LED was only just beginning to compete with traditional light sources. White LEDs were quite expensive, offered weak performance, and were technology driven rather than application oriented. The early adopters made portable lamps, dental filling compound curing equipment or entertainment and architectural colour mixing luminaires. The design challenges were quite simple: get the light out and heat away. So, with only a few LEDs available in the market, lighting product manufacturers were hardly spoilt for choice. As an example, Future Lighting Solutions used to have only a handful of LUXEON LED parts on its line card. The few optics manufacturers of the past only needed to concern themselves with designing components to fit those few LEDs and the limited number of applications where they could be used.

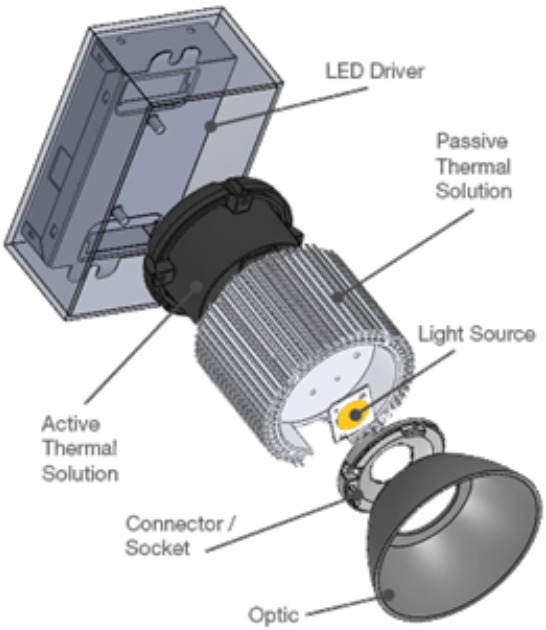

Figure 1: Product selectors are simple to use but not always sufficient for full system optimization.

Nowadays, the choices available to the lighting equipment designer are ever more numerous. This means that there are more ways of achieving the same design objective than ever. And it is not as if the lighting components market is static and mature: in fact, the technology of LED lighting continues to develop at a phenomenal rate, and hundreds of new LEDs, light engines, drivers, reflectors, lenses, connectors, heat sinks and control modules are introduced to the market every year.

And while the LED has become the light source of choice in illumination, a large range of UV light applications is yet to convert to solid-state technology. With performance going up and cost going in the opposite direction, the LED is rapidly becoming a viable option. What is the tipping point? What is the time to 3-log bacterial inactivation using a UVC LED in a coffee machine's water tank? Dedicated calculation tools are needed to help the designer make a rapid assessment from their application's parameters. The same is true in horticultural lighting: how to convert LED lumens into Photometric Photon Flux, and from there to a Daily Light Integral that a growing lamp can deliver to the crop?

So, before the actual design work even starts, translating the system's specifications into LED requirements, identifying the associated components and assessing the feasibility of the end product can be a time consuming and risky exercise.

The interdependencies of parameters such as LED junction temperature, ambient temperature, drive current, thermal resistance of the heat sink, and lumen maintenance, combined with driver efficiency and optical losses, make the calculation of system performance a laborious process if performed manually. One simple change in one parameter could potentially force the equipment designer to consult the datasheet for every other component used in the design in order to calculate the impact on the system as a whole.

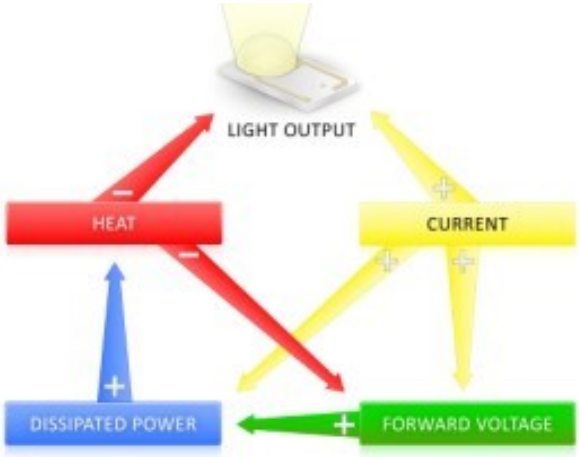

Figure 2: The interdependencies of LED operating parameters.

The lack of internal resource or the time to market pressure could induce a project manager to opt

for a turnkey off-the-shelf light engine. Still, one missing or suboptimal element in the combination of light source/optic/driver/thermal ecosystem can bring you back to square one.

More than ever, the industry needs sophisticated design automation tools: system “creators” to accelerate and simplify the selection of components, enabling the designer to answer “what if?” questions in order to quickly compare the benefits and trade-offs of different choices and configurations. The tools should be application specific simulators to calculate the light source requirements from the end application’s specifications and assess the feasibility of the end product. Also needed are dedicated single function tools to optimize specific parameters, predict performance and check design limits.

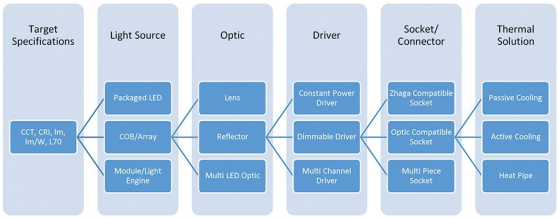

Figure 3: System “creators” help accelerate and simplify lighting design.

A large selection of tools is in fact already available on the market. LED performance simulators can be found on many manufacturers’ website. They are generally intuitive, easy to use and free of charge; they will occasionally include some ecosystem elements. Optics suppliers provide efficient component selectors starting from the LED light source and the application. They give quick access to mechanical and optical CAD models in industry standard formats, such as IGS, STP, IES or LDT. Driver manufacturers, surprisingly, offer quite limited support for product evaluation. Browsing the web, the engineer will also find multiple ad hoc calculation spreadsheets. These can be helpful, but it is important to double-check their accuracy and the limits of the conditions to which their results can be applied. Finally, specialized mechanical, thermal or optical CAD software packages support LED lighting design. They are, however, quite expensive and must be operated by trained engineers.

Component manufacturers are rightly focused on their product line, and CAD software companies on highly sophisticated algorithms that can serve as many different industries as possible.

Future Lighting Solutions believes that component distributors should also play a pivotal role in the product selection decision: Future Lighting Solutions offers easy-to-use design tools which allow the design engineer to concentrate on optimizing their product’s performance and value to the end user. They should help them deal with the increasing complexity of design decisions, reduce the risk of making a suboptimal choice, and make correct calculations of system parameters.

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Reinventing Office Lighting — The Making-of an Innovative Office Task Light

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Abstract

The office world is currently undergoing big changes. New concepts like shared offices, co-working spaces and a growing demand of home working models which are compliant to office standards are major challenges. The furniture industry is adapting to those requirements leaving the lighting Industry behind. Therefore it is time to find adequate lighting solutions for these new work models and environments. Looking at the complex demands of architecture and a user-centered office design, it is clear that the ceiling plane is not the most convenient place for the light fixture. The beloved freestanding luminaires have always been a crutch: Too big to be flexible, freestanding task lights add an undesirable new horizon into the open space and always lead to a struggle between users in terms of individually desired light quality.

With my presentation, I would like to display the development process of an innovative lighting concept leading to a new light fixture. The set of objectives for the new task light was to create an object which does not compete with the architectural concept of modern offices, to provide a fixture as flexible as a desk and a chair and to give the user the freedom of personalized light settings. The key asset of this concept is to illuminate the whole office from below the users' eye line. This leads to a small-sized fixture which is easy to handle and needs only a socket for power supply making the concept very flexible.

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The Challenge

The world of office working is changing, rigid structures are becoming more and more flexible, tasks more complex, and agile teams need the possibility to change group sizes and locations. The well-being of employees is in focus, especially within desk sharing concepts where the loss of a personal environment is a big topic (see Figure 1). This demands not only flexible and comfortable office equipment but also modern lighting concepts that combine excellent light with flexibility and individual control.

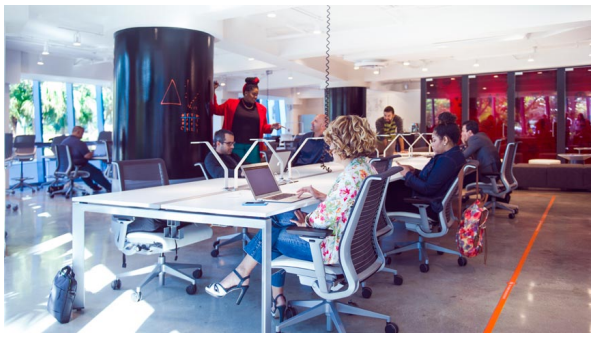

Figure 1: Coworking-office.

When considering complex demands of architecture, ranging from heated and chilled ceilings to the demand for total flexibility of the desk location, it becomes obvious that luminaires, which have a fixed location at the ceiling plain, cannot provide a satisfying solution.

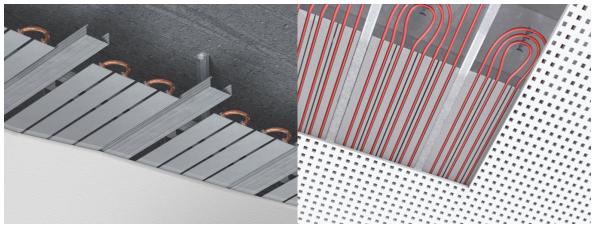

Figure 2: Ceiling systems.

The freestanding luminaire has never been ideal. Too big for a truly flexible solution as well as adding an undesirable horizon into the open space. Because the direct light of a freestanding luminaire always caters to a least two workstations, it can never provide individualized light quality.

The furniture industry is adapting to the new workspace requirements, leaving the lighting industry behind. Therefore it is time to find adequate lighting solutions for these new work models and environments.

Figure 3: Disturbing horizon.

The Idea

The idea was to create a new fixture, combining the strength of a free standing luminaires by providing a flexible room light, with the personalized light settings of a desktop luminaire. The fixture should not compete with the architectural concept of modern offices and should be as small and flexible as a laptop.

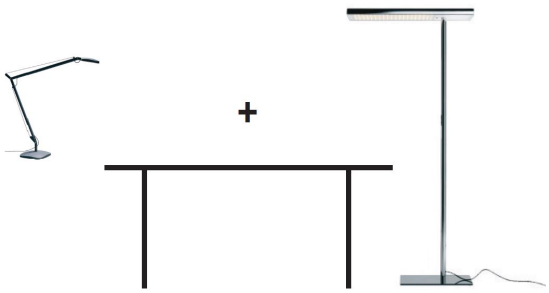

Figure 4: Idea.

The Concept

The goal was to develop a desktop luminaire that combines a personal direct and indirect light output. While the glare-free indirect uplighting component illuminates the complete office, the direct component should create a perfect light at the task. The idea was to allow users to set their personal lighting preferences individually directly on the luminaire or via an app. This combination should ensure that the light levels are compliant with standards, yet the luminaire is as flexible as a laptop and can deliver personal light settings.

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Figure 5: Concept.

Figure 6: Prototypes.

Bringing It All Together

To achieve all the different goals within this project, we had to use the whole cornucopia of possibilities which are provided by technology today. We used a mix of different optical materials, including thin film optics to ensure the glare control, a good mixing of different LED color temperatures, and sufficient power with high efficacy to comply with office and building standards.

Bluetooth low energy gave us a simple and future-proof solution for the communication between the luminaire and the users' smart device. The new BLE mesh protocol made it possible to build groups of luminaires to avoid a mixture of different color temperatures from the fixtures' indirect component, thereby preventing an office ceiling with spots of warm and cold white.

Two light sensors are built into the luminaire head. These ensure maximum energy savings during the day and a uniform ceiling illumination from multiple fixtures. A scalable HF motion sensor to make sure to have the possibility to customize the range of motion detection.

As electronic components continue to shrink, all necessary sensors could easily be located within the thin luminaire head. The custom developed app provides sophisticated control of all the various possibilities to individualize the light.

Way down the road — How can the goals be achieved?

The biggest challenge was to achieve a powerful yet glare free indirect component which is below the sight line of a standing person and positioned between computer screens.

Since the LED was introduced for general lighting, it has improved impressively in lumen efficacy and light quality. The extreme light density of the more and more powerful chips has led to bigger challenges to control the light and its glare. Lenses, reflectors, or diffuse housings are no longer the best solution to control light and reduce glare. The solution was found within the new field of thin film optics which are able to create a large area with a low light density in the critical degrees of 0°–30° while still achieving an output of 5000 lm in a precise angle toward the ceiling.

After the concept for the optics of indirect light had matured, the next challenge was the direct component. It soon became clear that this was first and foremost a challenge to the design of the luminaire. Every existing luminaire head that could be turned and tilted was a foreign body on the luminaire. The solution to maintain a thin luminaire profile, was a disk rotating parallel to the indirect light with an asymmetric light distribution. The parallelism of direct and indirect light, in combination with the height adjustment of the luminaire, led to an astonishing effect. When the lamp head was brought to the height of the eye line while sitting, one was in a bright room with a perfectly illuminated table without seeing a single light source.

Developing the electronics and the app with the user interface in mind was the source of a lot of concept work in the beginning. From the start, the task was to outline the use of the luminaire as precisely as possible in order to define the required functions and sensors.

Although the possibilities to control the light via a smartphone or a smartwatch lead to completely new possibilities for the individual user,it was important to enable the most important functions via three physical buttons. Even today, not

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everyone wants to control their light via a smart phone.

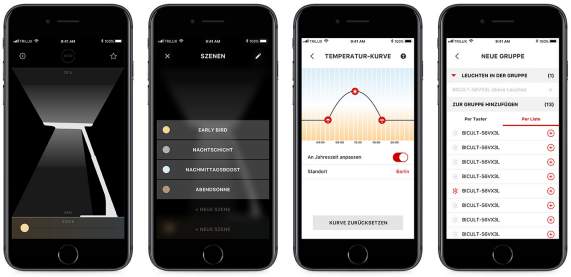

Figure 7: Bicult app.

- Diming and changing the color temperature of the direct and indirect light
- Managing of personal scenes
- Adapting of HCL curve to personal preferences
- Grouping luminaires to synchronise the indirect components
- Implementation of sensor settings

Final Result Displayed At Light And Building 2018

After 1.5 years of design and development, the target for Light and Building 2018 was not only to show a prototype of the luminaire, but to present a product that was immediately available to the public. With great effort and an impressive synergy between the Licht Kunst Licht and Trilux teams, it was possible to present the first finished products at the fair. Since the fair, more and more offices have been supplied with the luminaire and the feedback from users has been overwhelmingly positive. Despite higher than recommended ceiling heights, this new type of office lighting is also currently being tested in our office and has been rated very positively by my critical planner colleagues.

Study at the University of Applied Sciences and Arts Hildesheim

If you bring something new to the market that doesn't exist yet, you are of course always extremely curious how the product will be accepted. Apart from the positive feedback from customers, colleagues, and competitors, it was very interesting that Florian Ahrens from the

Figure 8: Bicult luminaire.

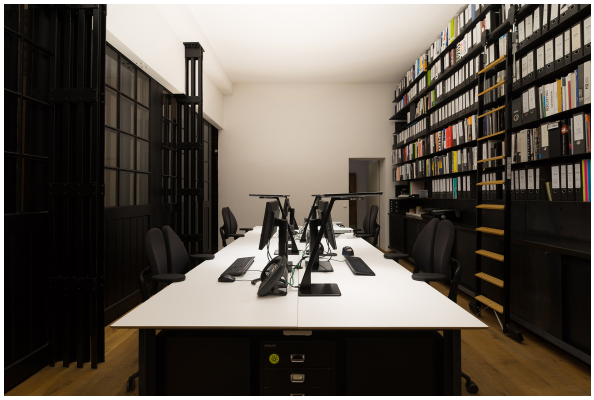

Figure 9: Bicult luminaire.

University of Applied Sciences and Arts Hildesheim dedicated his bachelor thesis to the topic of office lighting for new working environments. In his work, different types of office lighting were tested and compared in a test room and evaluated by study participants.

Figure 10: The Bicult Luminare in the test environment with deferent color temperatures.

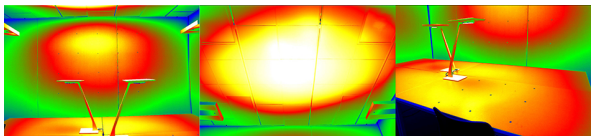

Figure 11: luminance images of table, ceiling, and wall.

The Bicult luminaire was rated very positively and was generally the preferred workplace lighting. The high indirect light output and the relatively low mounting height of the table lamp constructs an attentive,interesting, attractive and bright room. What was particularly interesting was the commentary that this type of lighting contributed

to a feeling of privacy; an important aspect in the rather public environment of an open-plan office.

Another interesting finding of this study was the evaluation of the brightness of the ceiling by the subjects. Current standards such as EN 12464-1 or ASR A3.4 are primarily concerned with the lux level in the field of visual tasks. The walls and ceiling are classified as much less important. The results of the study have shown that the ceiling is the most important influence on the person at the workplace. Attention must not be fixated+ only at the center of the retina (fovea),stimulus can also be triggered in the area of peripheral vision as well.

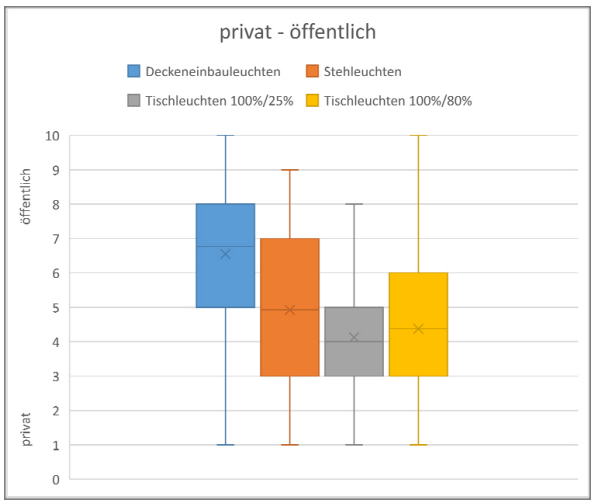

Figure 12: private — public

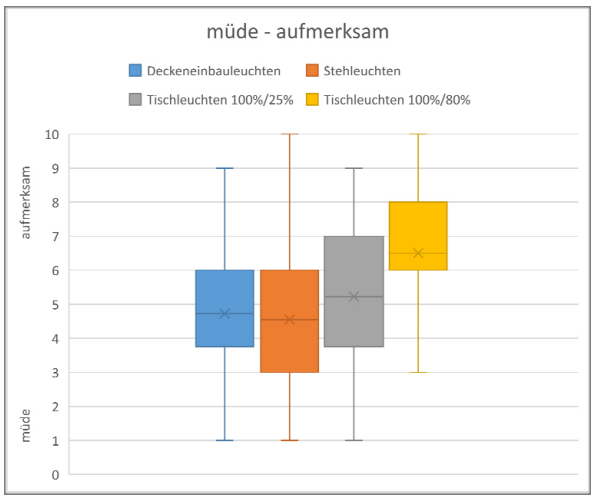

Figure 13: tired — attentive

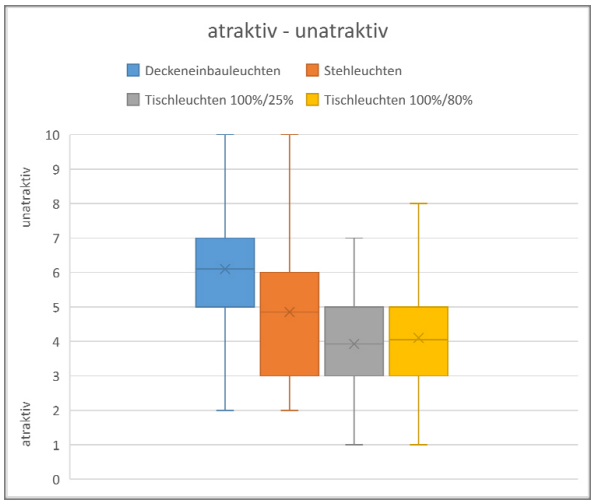

Figure 14: attractive — unattractive

Foto Credits

Fig. 1: Axis-space-coworking-office

Fig. 2: Knauf Gips KG

Fig. 3: Regent

Fig. 4: Till Armbruester

Fig. 5: Till Armbruester

Fig. 6: Till Armbruester

Fig. 7: Trilux

Fig. 8: Trilux

Fig. 9: Johannes Roloff

Fig. 12: Florian Ahrens

Fig. 13: Florian Ahrens

Fig. 14: Florian Ahrens

Fig. 11: Florian Ahrens

Fig. 10: Florian Ahrens

References

[1] Buerobeleuchtung neuer Arbeitswelten Lichtrichtung und Leuchtdichten im Raum als Indikator des Wohlbefindens. HAWK Hochschule für angewandte Wissenschaft und Kunst Hildesheim/Holzminden/Göttingen Fakultät Gestaltung Lighting Design Bachelorarbeit Sommersemester 2018 Florian Ahrens Matrikel- Nr. 612715.

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Injection Moulded Diffraction Gratings on Curved Surfaces. A Breakthrough for a Cost-Effective Industrial Mass-Production

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Austria

Abstract

As an example of the applicable process chain, a concave grating (1175 grooves/mm) with an active area of approx. 24 mm to 24 mm has been replicated by means of electroplating and further by injection moulding with polycarbonate, resulting in a surface accuracy even below 4 µm peak-to-valley (PV). The obtained moulds were further metallised with bare aluminium to obtain components for optical applications. To our knowledge, this is the first time that such a large nanostructured nonplanar surface has been manufactured by injection moulding in such an accuracy.

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Introduction

The importance of nanostructured surfaces is strongly gaining importance. More and more conferences, funding programs and publications are dealing with this topic confirming its increasing interest. Nanostructures can help to enhance the functionality of surfaces/devices, reduce building volumes, substitute additional coatings and therefore, reduce the costs of production or they can even add new functions.

Beside hot-embossing and nanoimprint lithography, injection moulding is another very potent high-volume production technique which is also capable to reproduce micro- and nanostructures, e.g., for optical storage media. In general, the production of structured nonplanar surfaces is a rarity because of the high demands on accuracy. This is even more true for injection moulding, since the required nanostructured tools have to be made of hardwearing metals.

Therefore, a conventionally fabricated master of a concave diffraction grating was replicated in nickel by electroplating and this tough high-precision casted insert was transferred into an injection compression tool for further replication into plastic. The quality of the replications was confirmed by optical microscopy, wavefront measurements, scanning-electron-microscopy and application.

State of the art

Micro- and nanostructures are commonly prepared by various lithographic methods, with and without masks, by light, electron-beam or even ion-beam.[1] Additionally, etching can also be applied to develop the structures or to generate very small geometries, such as moth-eye structures.[2] Another approach is the self-assembling of particles or molecules, even down to some nm. Established cutting techniques can also be applied, e.g., for micro-lenses, Fresnel-lenses, etc. but the accuracy is limited to few µm and the manufacturable sizes and geometries are strictly dependent on the dimensions of the employed tools. Nowadays, additive manufacturing, such as 2-photon-polymerisation, can also be applied to prepare structures even below the µm-range.[3] However, with those techniques, only single parts can be made.

Hot-embossing, nanoimprint lithography (NIL) and injection moulding are mass-production processes which are capable to reproduce micro- and nanostructures and are commonly applied for planar structured surfaces.[4] Hot-embossing and NIL are also dependent on substrates like foils or plates and therefore 3D-macroscopic geometries are hard to realise.[5] Hence, injection moulding is superior when shaped geometries are aimed but the structuring of the required wear resistant metal tool inserts is very challenging. As mentioned, conventional tooling is limited in accuracy and by the tool geometries.[6] Laser ablation is a technique that can be applied directly, but obtaining smooth surfaces is a challenge because worn off material is likely to deposit on the surface.[7] Chemical or physical etching can also be applied, but the applicability is strictly dependent on the material, which also restricts the obtainable structures.

Since a long time, nickel electroplating is used for the casting of micro- and nanostructures, e.g., for optical storage media, decorative surfaces, etc. The obtained so-called shims are further used as tool inserts, e.g., for injection moulding or hot-embossing. The advantage of nickel electroplating is the hardness of the metal, the high accuracy of replication and the well controllable process operation.

Process chain and results

To apply the potential of high-precision injection moulding for the mass production of micro-/nanostructured devices, the required structured tool inserts can be manufactured from a nickel cast of a structured master. The master can be obtained from any process, which is capable to generate the required geometries and quality. For such components, not only the quality of the optical structure, but, maybe even more, the accuracy of the surface fitting is very important. Even 1 µm deviation in shape can have a big influence on efficiency and/or accuracy.

Here, the master (32 mm × 32 mm) of a concave sphere (radius 110.2 mm) with a blazed grating (1175 grooves/mm) and an active area of approx. 24 mm × 24 mm was replicated in nickel as a 4–5 mm thick plate. This first cast (= father) could have been applied as a tool insert because of its invers geometry of the master, but since the master is destroyed after electroplating, the father was copied again into a second nickel cast (= mother) which was replicated once more into a

third copy (= son) that was used as the tool inserts. With this approach, several copies of the father and mother are accessible. Due to the tool design, the son had to have a thickness of over 6 mm in the middle. Therefore, the electroplating process required several days. The surface accuracy of the nickel casts was measured by wavefront measurements (Table 1). It was observed, that the PV deviation of the surface fitting (compared to an ideal sphere of the corresponding radius) increased with every generation from below 0.5λ (master) up to 3.1λ (son), where λ = 632.8 nm, due to internal stress upon electroplating. In addition, the radius became smaller with every further generation. Sometimes, it was also observed that the fitting became better in the next generation and the pattern itself could get better after some copies. The shape of the misfit of an electroplated cast was always a saddle (see Figure 1, top right).

Table 1: Replication accuracies.

Sample	Fitting PV [λ]	Radius [mm]
Master	0.3–0.5	110.2
Father	0.5–1.5	110.0
Mother	0.7–3.1	109.7
Son	1.0–3.1	109.3
Mould	6.5*	108.3*

* Average under applicable production conditions, tool insert with 3.1λ fitting.

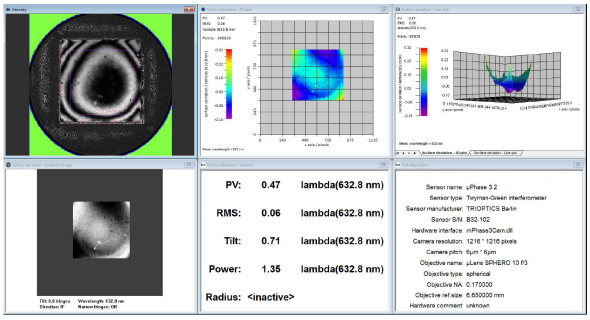

Figure 1: Wavefront topography measurement protocol of an electroplated cast (1st generation).

The moulding tool was conceived as an injection compression tool, because of the very high demands on the surface accuracy. The planned compression mode was also the reason for the thick and massive nickel inserts because the required pressures were expected to be very high. A heat channel was implemented to keep the material as long as possible at high temperature to ensure casting of the nanostructures and to bring the injection gate out of the middle axis, so that the compression forces are in the centre of the tool. To make sure that no liquid polymer is pushed back into the reciprocating screw upon compression the heat channel was equipped with a needle closure nozzle.

The process was simulated prior to tool construction by Autodesk Moldflow® analysis to confirm the injection moulding process and the aimed accuracy within the active area. The simulation predicted no shrink marks within the active area (Figure 2).

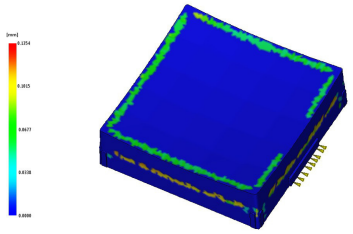

Figure 2: Moldflow® simulation of the moulding process predicting the expected local shrinkage.

The injection moulding was carried out with polycarbonate types of low viscosity and good demoulding properties on an Arburg Allrounder 370s injection moulding machine.

First production tests with a tool insert fitting of 3.1λ resulted in moulds of a fitting deviation (PV) of average 6.5λ and a radius of 108.3 mm. Surprisingly, changes of the compression pressures within a certain range had only small influence on the fitting but larger radii were obtained at higher pressures. However, too high pressures and too long compression resulted in demoulding problems and a demoulding spray could not be used because it filled up the grating preventing its complete casting. Additionally, with too high pressures a faster wearing of the inserts is likely.

Finally, coating of the plastic moulds with bare aluminium resulted in ready-to-use concave gratings. The metallisation revealed that the surface of the moulds was imperfect, appearing as cloudy shadows and enhancing the scattered light. These defects originated from the nickel insert, which was negatively affected by the required machining of the raw electroplated cast. This was also confirmed by microscope images before and after machining. Nevertheless, the plastic grating on the concave surface still had the capability to split white light into its spectral band confirming the functional replication of the grating (Figure 3).

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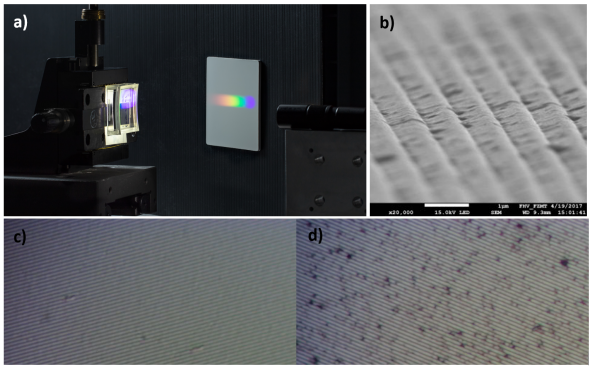

Figure 3: a) Diffraction effect of the uncoated concave plastic grating on white light, LED-flashlight as source; b) SEM image of the grating surface of a nickel cast; microscope images at 400× magnification of c) a raw electroplated cast and d) the final tool insert.

Conclusions

This process chain reveals that even large shaped surfaces with nanostructures can be replicated precisely into a nickel cast by electroplating. Such a cast of several mm thickness was further successfully transferred into an injection compression moulding tool with which applicable moulds could be produced under mass-production conditions. Sufficient protection of the nickel cast upon further machining will reduce the surface defects of the insert and therefore of the final moulds.

The now accessible polymer-gratings are an economic alternative to extensively produced glass based optical components and, to our knowledge, such an accuracy in injection moulding has not been reported yet on such large and structured areas.

Acknowledgment

We would like to thank our customer, who entrusted the R&D department of kdg opticomp with this challenging task, for their confidence and appreciative cooperation. We also thank the FH Vorarlberg, Institute of Microtechnologie for scanning electron microscope measurements.

References

[1] Levison, Harry J., Principles of Lithography, 3rd edition, SPIE Press, Bellingham, 2011.
[2] Z. Diao *et al.* ACS Omega, 2017, 2 (8), pp 5012–5018.
[3] Baldacchini, Tommaso, Three-Dimensional Microfabrication Using Two-Photon Polymerization, 1st edition, Elsevier, Oxford, 2015.
[4] H. Schift, J. Vac. Sci. Technol. B., 2008, 26, 458–480.
[5] T. Koepplmayr *et al.* 2015 Surf. Topogr.: Metrol. Prop. 3 024003.
[6] EU-funded research project LAUNCH-MICRO, funding number NMP2-CT-2005-011795.
[7] Ch. Hopmann *et al.* AIP Conference Proceedings 1664, 110003 (2015); doi: 10.1063/1.4918478.

A New Approach to Optical Beam Shaping for Lighting Applications based on Nano-Optics

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Abstract

In this paper a new revolutionary approach to optical beam shaping for lighting applications is presented. The optical devices, developed by IQ Structures under the trade name Nanoptiqs are based on principles of diffraction, which are applied in a novel way to achieve improved performance of white light illumination systems. This unique solution is based on full control over the modulation of material and geometric properties of the optical elements at a nano-level. The surface (or volume) properties of the micro/nano structured optics are calculated with details as small as 10 nanometres, generally in three-dimensions. High complexity modeling of the light interaction with matter at nano-scale makes this task extremely computationally intensive. Moreover, manufacturing of three-dimensional optical nano-structures requires application of state-of-the-art mastering techniques with extreme spatial resolution such as electron-beam lithography, direct-writing based on multi-photon absorption and similar. These techniques together with in-house developed computational tools and high-precision mass-replication technologies stand behind Nanoptiqs unique properties, which promise an important role with these products not only in laboratory applications, but also in high capacity industrial production.

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Introduction

For a long time light in luminaires was generated by incandescent and fluorescent sources. Because of large dimensions of light-emitting areas, the beam shaping systems applicable with these sources were always bulky. With the invention of LED sources and their rapid development during the last decade the light-emitting volume decreased significantly and simple replacement of old light sources with LEDs in original fixtures became unreasonable [1]. Simultaneously, point-like nature of LED sources resulted in significantly improved spatial coherence of emitted light in place of beam shaping elements. For such light sources it became possible to apply a completely new approach to beam shaping based on diffractive elements. Although diffraction is intrinsically present in all optical systems, highly organized (coherent) light is required when the diffraction is used extensively as in optical holography or similar applications. On the other hand diffractive approach brings much more complex functionality and higher versatility while the diffractive elements are usually thin, light-weight and more effective in mass-production.

However, an idea of applying some types of micro-structures for shaping light beams in luminaires instead of conventional optical elements is already used for many decades. Existing solutions usually rely on something called “micro-prismatic” optics, where tiny optical prisms are used to deflect the light into a required direction. The micro-structure of elements is rather simple, very often linear systems of prisms are used. Some manufacturers also use spherical or cylindrical Fresnel lenses. From the point of view of elementary optical principles these elements work more with refraction than with diffraction of light. Typical dimension of micro-prisms is in tens of micrometers or even in hundreds of micrometers in lateral dimension and the depth of the micro-relief reaches similar values. In fact, these structures represent only a “miniaturized” version of macroscopic refractive elements with all positive and negative consequences. They are relatively efficient, more or less achromatic, but rather thick and simpler in function, less effective in mass-production and not capable of achieving complicated light distributions. The diffraction of light is not primarily used in such an extensive way as in holographic applications.

In this contribution, applicability of various types of true diffractive elements in light shaping applications is discussed. On one side, high density thinner elements are very attractive from point of view of mass-production and complexity of optical function, on the other hand mastering of high resolution micro-structures (or sometimes even nano-structures) is a challenging process which requires application of extremely precise state-of-the-art technologies. Moreover, some issues such as strong dispersive behavior and high sensitivity of energetic efficiency to various parameters must be addressed, which were not an issue for micro-prismatic elements. In the following sections some innovative approaches to design and analysis of diffraction-based optical systems for luminaires are discussed with focus on applicability for commonly used white LED sources. These approaches have been developed by IQ Structures s.r.o. and they are currently represented by a group of products under the trade name Nanoptiqs. Furthermore, manufacturing approaches to mastering and mass-production of the Nanoptiqs elements are also discussed.

Design approaches

In general, application of diffraction principles for beam shaping requires a different approach to design of luminaire optics. Commonly used ray-tracing techniques may become insufficient as they do not consider effects following from phase synchronization of light over larger areas of optical surfaces. Simple reflection and refraction effects (which take into account only local phase properties of light beams at smooth interfaces between optical elements and free space) must be supplemented with diffraction effects. Once an interface of optical element is micro- and/or nano-structured, the description of interaction of light with matter is very complex and simple ray-tracing approach becomes insufficient. One of the possible ways for designing diffraction-based systems is application of true wave-optical techniques based on wavefront propagation. This idea is schematically depicted in Fig. 1.

The approach automatically considers wave nature of propagating light and includes coherent effects such as diffraction and interference. Moreover, the target light distribution can be very general and can contain complicated features such as sharp edges, steep variations of light intensity and similar. However, propagation of

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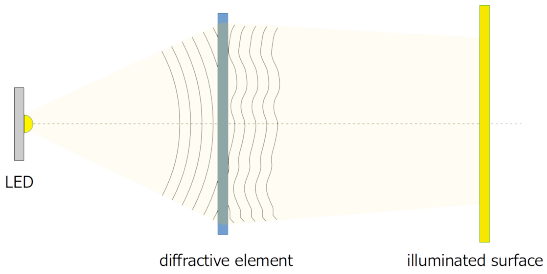

Figure 1: Wave-optical approach to the design of optical system. A wavefront generated by the LED is propagated considering phase properties within a single computational step.

complex optical wavefronts is a computationally intensive task and it is virtually impossible to simulate complete optical system of today's luminaires purely using wave-optical approach. The problem becomes especially tricky when a white light source is used with continuous spectrum of wavelengths. Moreover, although light-emitting volume of LEDs is much smaller than the volume of conventional sources, finite dimensions of LED's surface limit spatial coherence of light at the plane of optical element and make calculations even more challenging. Thus it is advantageous to combine ray-tracing techniques with rigorous modeling of the interaction of light with the optical structure (Fig. 2).

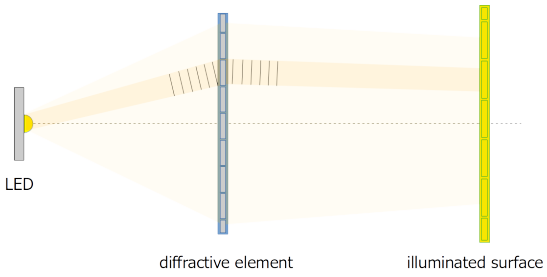

Figure 2: Hybrid approach is based on ray-tracing combined with rigorous treatment of the interaction of light with a micro- or nano-structured optical element.

Such an approach enables the use of widely available software tools for simulating most components of the luminaire except for modeling the interaction with optical micro- or nano-structures. Thus it is necessary to modify these tools and append such functionality to the design loop. Simpler description of light propagation speeds up the process and also brings more freedom to mapping of particular areas on the optical surface to particular parts of illuminated space. However, in case of complicated design the calculations can be still demanding.

Diffractive elements for white light

One of the issues which needs to be analyzed in detail is suppression of dispersion effects typical for diffractive systems. A diffractive dispersion is significantly stronger (and of opposite sign) than the material dispersion of common optical materials. When a typical feature size falls down to micrometer level or even below and the deflection angles are large, the distortion caused by color dispersion is critical. There are in principle three different ways how to deal with unwanted dispersion. The first is to blur the beams using some kind of diffusion and mix spatially separated color components back to create white light. Although such an effect is present in most systems, it is going against our primary idea of complex beam shaping and creating complicated light distributions. The second technique is oriented on intentional mixing of particular color components by managing each component independently. However, such an approach is more suitable for systems with separated color sources and for true white LEDs it is quite tricky to treat spectral colors separately. The third technique is based on operating the diffractive elements in higher diffraction orders. The basic idea of higher-order functionality can be demonstrated on a simplified example of blazed grating. Deflection of light after interaction with transmission blazed grating (see Fig. 3) is described by grating equation:

$$\sin \alpha_{dm} = \sin \alpha_i + m\frac{\lambda}{\Lambda}, \tag{1}$$

where α_i is an angle of incidence, m stands for the m-th diffraction order, λ is a wavelength of used light, Λ is a period of the grating, and α_{dm} is an angle of diffraction of the m-th diffraction order. For a thin blazed grating the diffraction efficiency of the m-th diffraction order is:

$$\eta_m = \mathrm{sinc}\left(m - \frac{\Phi}{2\pi}\right) = \mathrm{sinc}\left(m - \frac{n-1}{\lambda}d\right), \tag{2}$$

where n is a refractive index of the material of the grating and d is a depth of the relief (for simplicity the refractive index is assumed to be 1 outside of the grating).

If the grating from Fig. 3 is illuminated with white light (for simplicity represented with three color

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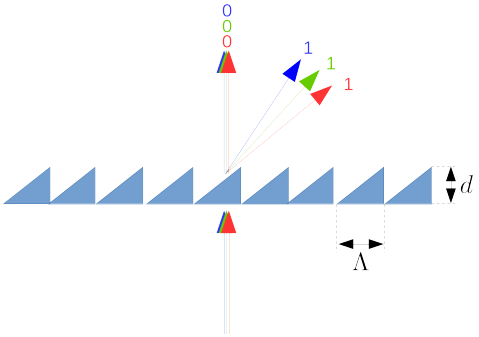

Figure 3: Diffraction from blazed grating operating in the first diffraction order. Because of strong grating dispersion, particular color components are diffracting with high efficiency in different directions and the outgoing beam is blurred in rainbow colors.

components r-red, g-green, b-blue), and the depth of relief is tuned to reach maximum efficiency for the green component, then:

$$m = 1, \Lambda = \Lambda_0, \alpha_i = 0,$$
$$\eta_{1g} = 1, \eta_{1r}, \eta_{1b} < 1, \quad (3)$$
$$\sin\alpha_{1g} \neq \sin\alpha_{1r} \neq \sin\alpha_{1b}.$$

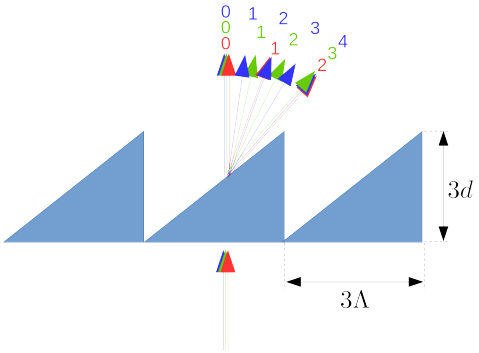

Figure 4: Diffraction from blazed grating operating in the third diffraction order. When the depth of the profile is properly tuned, particular color components from the white spectra diffract with high efficiency into different diffraction orders. Under some circumstances, these orders can propagate in the same direction and the outgoing beam is white — the diffraction is achromatic.

Therefore, strong dispersion effect appears. The diffracted light is blurred with significant chromatic aberration. In Fig. 4 there is a blazed grating operating in the third diffraction order, which is otherwise equivalent to the original grating from Fig. 3. Now, if 3-rd diffraction order is evaluated, we can write:

$$m = 3, \Lambda = 3\Lambda_0, \alpha_i = 0,$$
$$\lambda_r = \frac{3}{2}\lambda_g, \lambda_b = \frac{3}{4}\lambda_g \Rightarrow \eta_{3g} = \eta_{2r} = \eta_{4b} = 1, \quad (4)$$
$$\sin\alpha_{3g} = \sin\alpha_{2r} = \sin\alpha_{4b}.$$

To emphasize the demonstrated effect, specific relation was assumed between wavelengths of red, green, and blue components. For white light with continuous spectrum the relation is slightly more complicated, however, the resulting effect is similar. As it is clearly seen from equation (4), the 3-rd order grating exhibits fully achromatic behavior. Each color component diffracts in a different diffraction order, but absolute angle of diffraction is the same for all colors. Simultaneously, all components diffracts with maximum diffraction efficiency.

The presented example demonstrates achromatic behavior of higher order diffractive structures. Continuous refractive optical elements or micro-prismatic structures are just another examples of devices operating in extremely high diffraction orders. However, to achieve achromatic features based on a high-order operation it is not necessary to use deep elements working in the 100-th diffraction order or similar. In Fig. 5, there is an example of computer simulation of a beam shaping element creating a rectangular light distribution characteristic (see inset for the desired pattern).

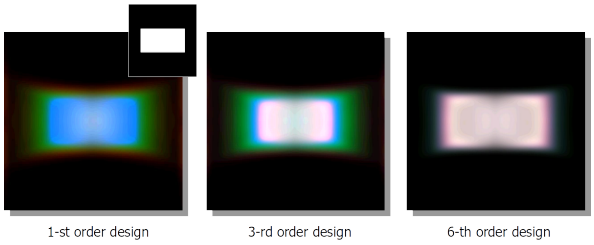

Figure 5: Simulation of dispersion effects for elements operating in different orders. The target light distribution is an achromatic rectangle (see inset). When the element is operating in the 1-st diffraction order (image on the left), the dispersion is strong. For element operating in the 3-rd order (image in the middle), the dispersion is already moderate. For the 6-th order element (image on the right), the dispersion is almost fully suppressed.

The dispersion is very strong for a 1-st order structure (image on the left), chromatic aberration is improved for a 3-rd order element (in the middle) and there is almost no distortion in a case of using a 6-th order structure (on the right). In fact, real experiments confirmed that in most cases it is fully sufficient to use the 3-rd order structure as the residual noise and other effects (that are always present) help to suppress remaining coloring.

Mapping approaches

When a hybrid approach is used which combines ray-tracing techniques with rigorous interaction of light with matter, one of the crucial steps is mapping of the optical element onto an illuminated area. Because particular areas of the optical element serve as beam deflectors, the deflection angle must be defined at each point of the element. Subsequently, a micro- or nano-structure can be designed which is capable of bending the light into a required direction. Because of complicated shapes in the illuminated area and the optical element itself such a mapping process can be complicated. The basic idea of mapping is depicted in Fig. 6. It should be noted here that both the target area and the optical element can become curved surfaces which makes the mapping even more challenging.

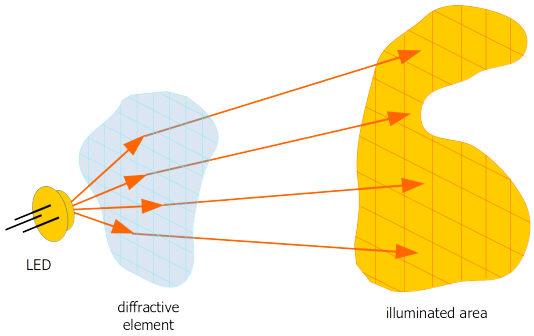

Figure 6: Simplified principle of direct mapping of an optical element onto the illuminated space. Particular areas on the element are assigned to the target areas in such a way that the deflection angle is minimized for all rays.

Although there are certainly many possible strategies for an optimum mapping, it is always advantageous to keep the deflection angle as small as possible at all points of the optical element. Minimizing the deflection leads to maximizing the feature size of the optical structure and consequently to optimizing the diffraction efficiency and demands on manufacturing process. However, sometimes there are specific design requirements which can affect a choice of the mapping strategy. One of such market-driven requirements is a homogenization of the luminous area of the luminaire for all relevant viewing angles. This practically means that each small area of an output aperture of the luminaire must send the light to all parts of the illuminated space. Such a requirement rapidly influences a micro- or nano-structure of the element. On the other hand, conventional optical systems simply cannot satisfy such requirements. In Fig. 7, there is a scheme of mapping which complies with the requirement of homogenized luminance over the output aperture.

A choice of the mapping strategy influences strongly properties of the micro-structure. In Fig. 8 there is an example of a micro-structure calculated using the direct mapping with a focus on minimizing the deflection angle at each point of the element. A continuous phase function (left image) is transformed to a diffractive form (image on the right) but resulting fringes of the micro-relief are still continuous.

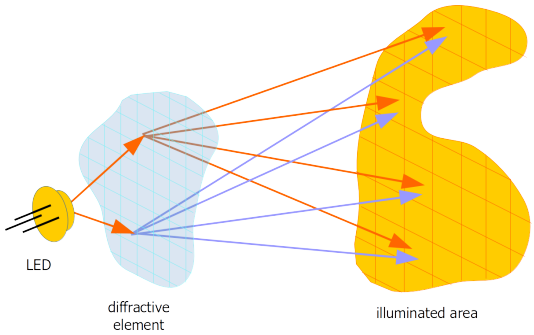

Figure 7: An advanced mapping scheme with a homogenized luminance over the output aperture of the optical system.

When the mapping strategy considers requirements on homogeneous luminance over the element, the micro-structure is different. In Fig. 9 there is an example of such an element based on blazed micro-gratings.

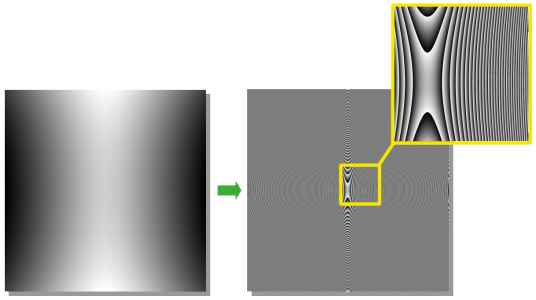

Figure 8: An example of a micro-structure calculated using the direct mapping algorithm according to Fig. 6. A continuous phase function of the element (on the left) is transformed to a diffractive element (on the right).

It is apparent that manufacturing demands are significantly different for elements from Fig. 8 and 9. However, an advantage of using the micro- or nano-structured elements in terms of flexibility and achieving a new functionality is clearly seen.

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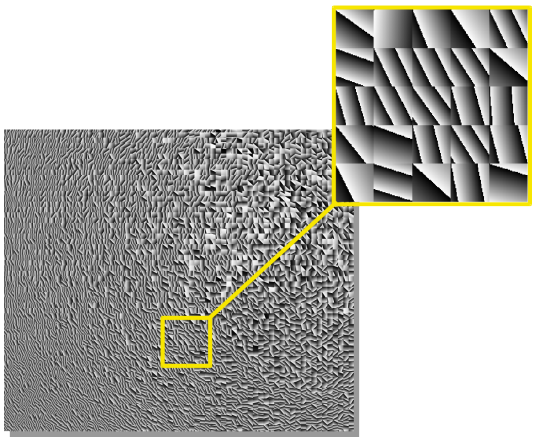

Figure 9: An example of micro-structure calculated using the advanced mapping according to Fig. 7. One of the possible approaches results in a system of micro-gratings with parameters rapidly varying over the element's surface.

Modeling the diffraction process

In equation (2) a simple model was used for evaluating the diffraction efficiency of the blazed grating. This model is based on an assumption of a thin grating which does not include volume synchronization effects. As a consequence the diffraction efficiency is independent of the angle of incidence and polarization of light. On the other hand, in real systems such relief gratings are for practical reasons already relatively "thick" and can demonstrate volume effects. Moreover, the depth of relief is even bigger when the micro-structure is designed for operation in higher diffraction orders. It is thus crucial to use more exact models for simulating the interaction of light with optical elements. In general, a more complex diffraction process must be taken into account as indicated in Fig. 10. An angle of incidence is varying (in real cases within a wide range because light beams from LEDs are highly divergent) and an existence of more diffraction orders must be considered.

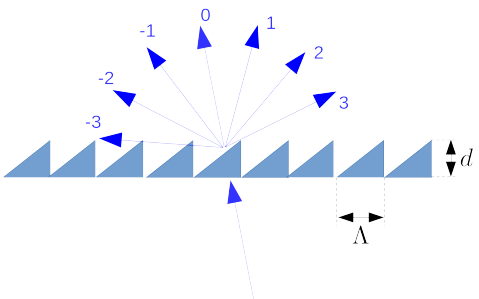

Figure 10: For real gratings, oblique incidence must be considered together with a presence of a wide system of the diffraction orders.

Various mathematical approaches can be used for more exact modeling of diffraction on optical micro- or nano-structures. Besides a direct numerical solution of Maxwell equations (which is hardly applicable for concerned optical systems in luminaires) it is possible to use methods based on Fourier modal techniques. One such method (originally developed for infinitely periodic elements) is the Rigorous Coupled Wave Analysis (RCWA). As a fully vectorial technique it takes into account general parameters of light and the micro-structure, it is applicable also for subwavelength nano-structures and it can be extended on aperiodic modulations [2]. Several commercial implementations of the algorithm exists, in this work a custom implementation was used which was modified exactly for the needs of design of optical systems for luminaires.

In Fig. 11 there is an example of application of the developed software tool in an analysis of the angular dependency of diffraction efficiency of a blazed grating. As it is seen, an optimum depth of profile strongly depends on the angle of incidence. Moreover, the absolute value of maximum efficiency is also varying. Such a result indicates critical problems for those parts of optical elements which are illuminated under high angles (typically areas far from optical axis of the beam for divergent beams). This issue must be considered during the design process of beam shaping systems otherwise the real diffraction efficiency will significantly decrease.

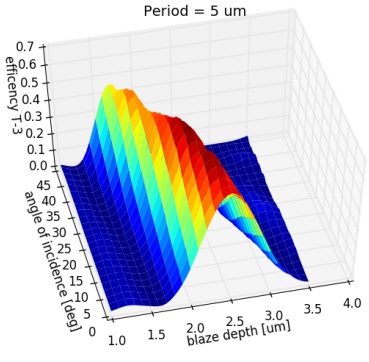

Figure 11: Dependency of the diffraction efficiency of the blazed grating on an angle of incidence and a depth of relief.

But the depth of profile is not the only important parameter which must be tuned. In a manufacturing process various distortions of a profile shape appear which can strongly influence an optical performance of the element. In Fig. 12 and 13 there is a dependency of the diffraction

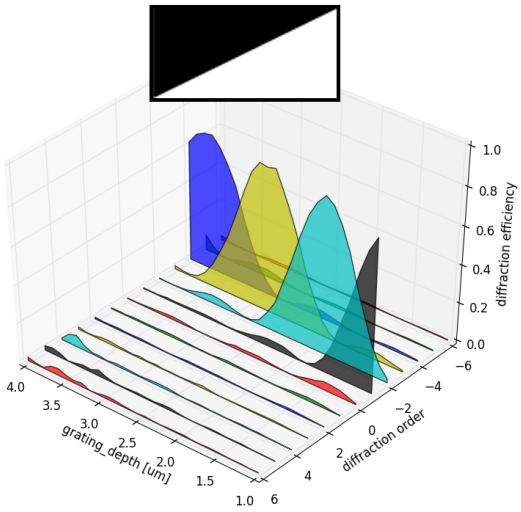

Figure 12: Dependency of diffraction efficiency of particular diffraction orders for an ideal-profile blazed grating on the depth of relief (see inset for profile shape).

efficiency of particular diffraction orders on the depth of profile for the exact triangular blazed grating profile (Fig. 12) and for a distorted profile from a real manufacturing process (Fig. 13). In both cases a normal incidence was assumed for simplicity. It is clearly seen that real profiles create many diffraction orders which must be considered within the design process. Peak diffraction efficiencies are also influenced.

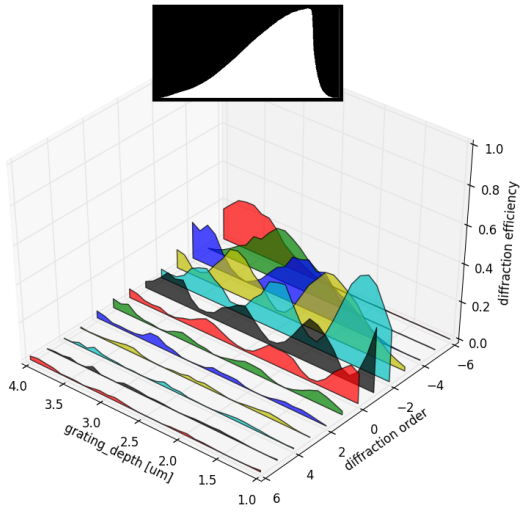

Figure 13: Dependency of diffraction efficiency of particular diffraction orders for a real-profile blazed grating on the depth of relief (see inset for profile shape).

Based on this analysis custom design tools were created which enables the design of optical elements and whole systems using real building units (manufactured and experimentally documented micro- and nano-structures). However, such calculations are extremely computationally intensive and requires a high level of optimization.

Multi-element optical systems

An idea of composing a luminaire just from an LED source and a single flat optical element is attractive, however, in most cases such a simple system cannot meet all requirements on the light distribution curve, overall efficiency or glare ratings. In real setups two main problems arise. First, flat thin optical elements cannot collect a sufficient portion of light emitted by the LED source, especially to higher angles. Second, it could be physically impossible to achieve larger deflection angles with a single thin element, if needed. In such situations an application of multiple optical structures could be advantageous also if they bring further absorption and reflection loses. An improved functionality can fully compensate for these disadvantages.

The Nanoptiqs solution developed by IQ Structures is a complex approach to design and manufacturing of multi-element optical systems for luminaires. A main goal of the Nanoptiqs elements is to simultaneously improve a performance and effectiveness of manufacturing of optical systems for luminaires. In conventional optical systems for luminaires a collection of light from large solid angles is ensured by some kind of reflectors. From a principal point of view the reflectors can be based on a reflection of light from a metallic layer (aluminum reflectors made by mechanical machining or injection-molded plastic reflectors with a metallic surface) or on a total internal reflection (injection molded TIR reflectors). However, both of these solutions dramatically devalue the effectiveness of systems based on micro- or nano-structured optics, because a production of such components is ineffective. Moreover, when the whole system is miniaturized (typically for low-profile luminaires), a beam shaping capability of the reflector is rather limited (direct light from the source does not touch the reflector and it is virtually impossible to achieve highly directional lighting). The Nanoptiqs systems rely on optical components exclusively based on thin-substrate elements (typically only carrier materials with thicknesses below 500 μm

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are used). To achieve the required optical functionality some of the elements must be curved (or have a general three-dimensional shape), some of them must be equipped with a micro- and/or nano-structure, some of them could be metallized. In case of a multi-element system some of the optical interfaces can be provided with some type of anti-reflection layers. In Fig. 14 a schematic drawing of a multi-element system comprising a micro-reflector and a nano-structured transmission element is presented.

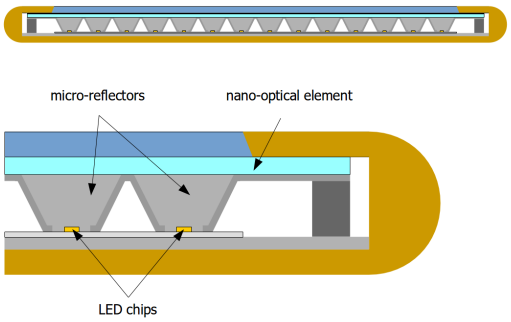

Figure 14: Schematic drawing of a luminaire using combination of micro-reflectors and nano-optical element.

Here the reflector is precisely shaped to collect light and pre-process it for the nano-optical element which is responsible for fine-tuning the light distribution characteristic.

Manufacturing

As it is clear from previous sections, manufacturing of the Nanoptiqs optical elements is a challenging task with high demands on the resolution and quality of optical surfaces. Simultaneously, all manufacturing steps must be compatible with high-throughput mass-production processes. The manufacturing thus can be divided into two parts: a mastering process which can produce primary micro- or nano-structured elements as a tools for further processing and a mass-replication process which is capable of an effective large-volume production.

Mastering techniques

There are several groups of techniques used for a production of optical diffractive micro-structures. An application of particular approaches strongly depends on a shape of profile of the structure, a feature size and other parameters. For optical elements with larger features and the depth of profile diamond turning techniques can be used [3]. A quality of produced elements in terms of micro-roughness, shape of profile or exact dimension of features is usually very high especially for linear or rotationally symmetric structures. However, single point diamond turning (SPDT) approaches are usually applicable only for elements with a feature size down to approx. 10 micrometers. For finer details it is difficult to achieve a sufficient surface quality and various artifacts can appear. For fully two- or three-dimensional structures (presented for example in Fig. 9) it is virtually impossible to use diamond turning mastering techniques.

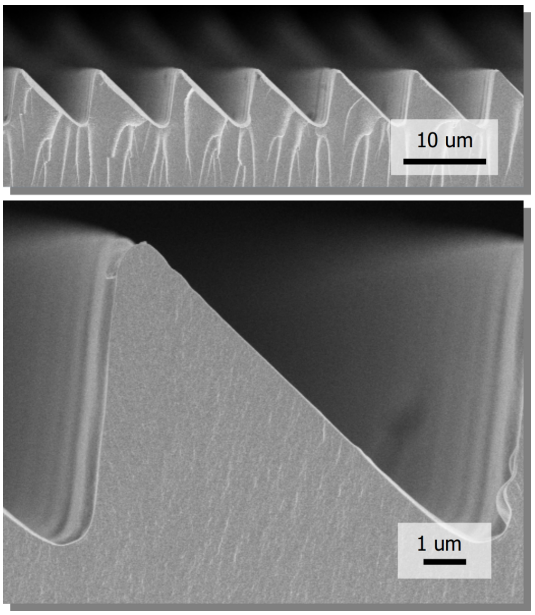

Figure 15: An example of a micro-structure prepared using the multi-photon absorption technique.

The second large group of approaches potentially applicable in the mastering of optical micro-structures comprises techniques based on direct laser writing. A single-point or matrix writing methods are well known from holography and similar fields [4]. A main advantage of these approaches is a high speed of exposure, an applicability of optical interference effects (interference lithography — an exposure of the recording material with a continuous three-dimensional interference field of two or more beams) and a capability of “gray-scale” writing (creating continuous relief profiles). A typical drawback of these techniques is a limited resolution due to the diffraction limit. However, for systems based on a multi-photon absorption, the resolution can be significantly improved together with a capability of creating general

three-dimensional features (see Fig. 15 and 16 for examples). In Fig. 17 there is an example of an optical micro-structure manufactured using the advanced matrix-laser writing technique.

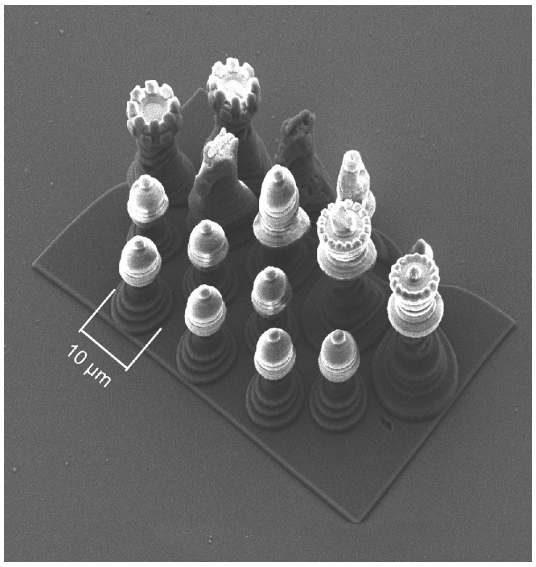

Figure 16: Demonstration of capabilities of a laser writing based on the multi-photon absorption.

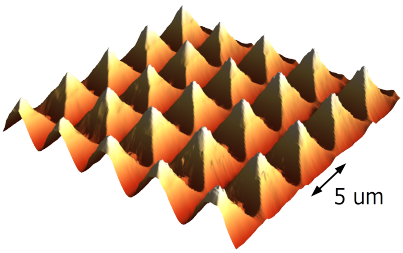

Figure 17: An example of a micro-structure prepared using the advanced matrix direct laser writing.

Sometimes, an extreme lateral resolution is required in a combination with general deep relief profiles. For such purposes a specially modified electron-beam writing processes can be used [5]. In Fig. 18 there is an example of a deep relief structure prepared using electron-beam lithography.

Mass-production

The main concept of Nanoptiqs systems is based on an effective mass production of particular optical elements. A key factor is an exclusive use of thin plastic layers (foils) which are originally flat and in one of the processing steps they are equipped with a micro- or nano-structure and/or formed into a general three dimensional shape. For tooling purposes a wide variety of electro-forming processes can be used together

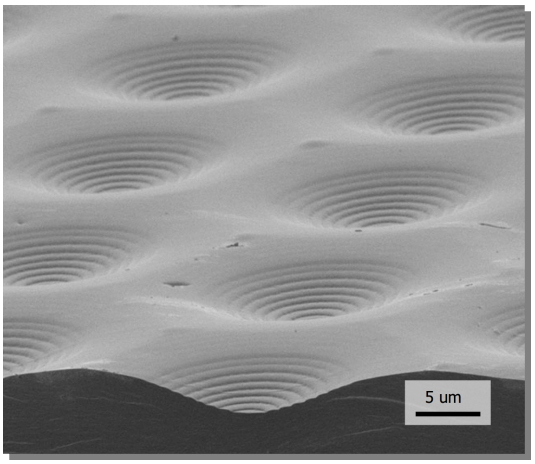

Figure 18: An example of a micro-structure prepared using the electron-beam lithography.

with nano-imprint techniques. A choice of applicable mass-production technology depends on many factors such as the shape of profile of the micro-relief, depth of the structure, aspect ratio, required final material and also a total volume of products. Most Nanoptiqs components can be produced in some form of roll-to-roll process which are typically extremely fast and effective. An optical relief is transferred using various combinations of embossing and imprint techniques.

Examples

The presented Nanoptiqs solution brings several revolutionary innovations into a construction of luminaires. First of all, the developed optical systems have low weight and they are produced using highly effective mass-production processes. The second advantage lies in a new functionality which is not achievable with conventional beam shaping systems. And, last but not least, the Nanoptiqs solution opens new possibilities in a luminaire design. Unlike the conventional optical elements, the shape and visual appearance of Nanoptiqs elements are not necessarily connected with their optical function. Such property can be used for tuning the appearance of luminaires in on and off states without influencing the beam shaping capabilities. Furthermore, a geometry of the whole luminaire becomes very flexible. It is possible to design extreme low-profile fixtures or another minimalistic configurations. In Fig. 19 there is an example of a luminaire based on Nanoptiqs elements. It is a surface-emitting low-glare device with a homogenized luminance over a large output aperture with a wall-washing function. Such combination of features is virtually

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impossible to achieve using conventional approaches.

Figure 19: An example of a surface-emitting low-glare low-profile luminaire with a wall-washing function based on the Nanoptiqs elements.

In Fig. 20 there is an example of a prototype system with a very complex light distribution curve (in a form of letter “M”, image on the left). Again, the luminance is highly homogenized over the output aperture (image on the right).

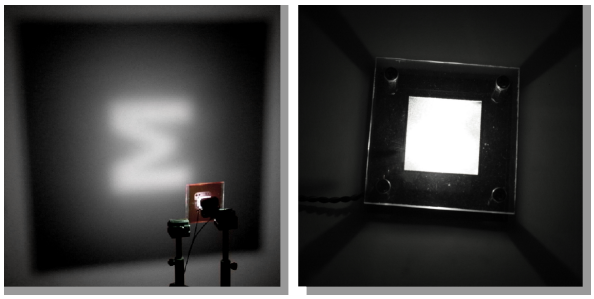

Figure 20: Demonstration of capability to achieve a complex light distribution from homogenized light-emitting surfaces.

Conclusions

In this paper a new approach to general optical beam shaping in luminaires was presented based on diffraction principles. The Nanoptiqs elements bring not only a significantly extended functionality, but also a highly improved effectiveness of mass-production. Completely new high-efficiency low-glare fixtures can be created with more freedom in the shape and visual design. The intelligent micro- and nano-structures open new capabilities to the luminaire industry. The sophisticated computer design together with the state-of-the-art manufacturing technology result in a new generation of optical systems for 21-st century.

Acknowledgment

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References

[1] T. Q. Khan, P. Bodrogi, Q. T. Vinh, H. Winkler, LED Lighting: Technology and Perception, Wiley-VCH, 2015.

[2] M. G. Moharam, Drew A. Pommet, Eric B. Grann, and T. K. Gaylord, “Stable implementation of the rigorous coupled-wave analysis for surface-relief gratings: enhanced transmittance matrix approach,” *J. Opt. Soc. Am. A* vol. 12, pp. 1077–1086, 1995.

[3] S. Suet To, Wang V.H., Lee W.B., “Single Point Diamond Turning Technology,” In: Materials Characterisation and Mechanism of Micro-Cutting in Ultra-Precision Diamond Turning, Springer, Berlin, Heidelberg, 2018.

[4] M. Škereň, J. Svoboda, and P. Fiala, “Advanced matrix laser lithography for fabrication of photonic micro-structures,” *Journal of the European Optical Society-Rapid publications*, vol. 7, 2012.

[5] S. Landis, Lithography, John Wiley and Sons, 2013.

Rapid Prototyping of Complex 3D Optical Components

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Abstract

In this work, we report on a method for fabricating unique optical components, which exemplify the concept of “micro on 3D macro” Additive manufacturing by 3D-printing, UV-soft lithography and lab-scale injection molding are combined into one process chain in order to realize such optical components. The method relies on creating the master by first using additive manufacturing and UV-based nanoimprint lithography (UV-NIL). Whereas 3D printing is applied to create the 3D macro object, maskless direct laser write lithography, followed up with UV-NIL is used to fabricate the microstructures on the printouts. The plastic optical components are then fabricated by means of lab-scale injection molding. The specific fabrication steps are discussed to point out the critical issues such as obtaining an optically smooth surface for the application in the field of optics. As an example, a squared optical prism with an integrated 1D diffraction grating on its surface is highlighted. The optical component is characterised by means of optical and atomic force microscopy. In conclusion, possibilities of the “micro on 3D macro” concept for low-cost fabrication of plastic optics are considered.

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Introduction

Nowadays complex 3D optical components incorporating structures of (sub-) micrometre feature sizes on the surface of bulk optics have become attractive in many diverse applications. Such examples (see [1][2]) can be found in optoelectronics, photonics, image processing, machine vision and motion control systems. Adding an optical functionality to the surface of bulk 3D optics through integrated (sub-) microstructures has the potential to contribute substantially to the miniaturization of optical components, to improve the integration into a system and obtain lower prices. Nevertheless, the development of such complex 3D optical components with novel functionalities poses some technological challenges both in design and in fabrication.

The implementation of a (sub-) microscale structure on the surface of centimetre wide bulk optics is the main challenge in manufacturing such a hybrid optical component. To enable cost efficient manufacturing and meet the claims on surface quality and shape accuracy, several fabrication methods are usually combined into one process chain. An efficient way to fabricate the (sub-) microstructure is the use of optical lithography. In this field, the maskless direct laser write lithography (MALA) offers a method which confederates precision and writing speed [3]. It allows for the creation of 1D, 2D and continuous relief structures (2.5D) with complex optical geometries, e.g., free form micro optics [4]. Moreover, the fabricated microstructures are optically smooth with an arithmetic average roughness height of Ra $< \lambda/16$.

In this work, we show a preliminary study to prove the principle of a novel approach to create a hybrid 3D optical plastic component. The presented preliminary concept of “micro on 3D macro” is based on the combination of 3D printing, MALA, UV-nanoimprint lithography (UV-NIL) and lab-scale injection molding.

Fabrication method

As depicted in Figure 1, the process flow used to fabricate the hybrid 3D optical plastic component relies on the combination of four technologies; 3D printing as additive manufacturing, MALA, UV-NIL [5] and lab-scale injection molding. Firstly, the 3D macro object is created by 3D printing followed by a post-treatment step to rework the surface. The next step is the fabrication of the (sub-) microstructures on a silicon wafer coated with a photosensitive material by laser writing. The following UV-NIL is used to transfer the (sub-) microstructures onto the printout. Next, a silicone 3D elastomeric mold is created from the printout with the integrated (sub-) microstructures. The last step is the fabrication of the complex 3D optical component, by injecting an optically transparent liquid material into the silicone 3D mold and a curing process to harden the material.

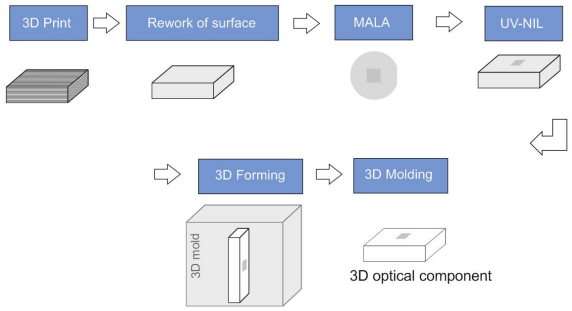

Figure 1: Schematic representation of the fabrication chain for complex 3D plastic optical components.

To fabricate the 3D macro object, an *Objet30 Pro* 3D-printer (*Stratasys*) was used. It has a build resolution of 600 × 600 × 900 dpi (X/Y/Z) and a layer thickness of about 28 µm. The 3D printing process is based on the Multijet Modeling (MJM) technique, which uses an inkjet print head to spray a thin layer of a UV-curable resin (photoresin) layer-by-layer onto a build tray. After each printing step the layer is fully cured by a UV light, therefor the produced devices can be used immediately. All samples were printed with *VeroBlack Plus* in glossy mode to enable the smoothest possible surface after printing. The surface roughness of 3D parts fabricated by MJM is very low but still does not fulfill the high requirements in optics. Therefore, the surfaces were mechanically polished by the use of a *Struers Labopol-5*. In order to obtain a high-gloss polished surface, a typical polishing procedure (fine grinding/polishing/lapping) was used.

The in-house built MALA was used to write the 1D diffraction grating on a photoresist (AZ4562, *MicroChemicals*) coated two-inch Si-wafer. In our previous work [4] a detailed description of the MALA system can be found. During the writing process of all individual lines of the grating it is necessary to keep the laser focused on the surface of the sample. In order to achieve that, all axes move simultaneously in a predefined trace.

The possible tilting of the sample with respect to the laser beam was compensated by conversion of the data to be written. To determine the laser focus position in axial direction, a confocal detector, which is a part of the MALA system, was used.

To transfer the microstructure pattern written on the silicon wafer onto the surface of the cast, the UV-NIL was employed. The *NILcure*^{TM} photoresist was dropped onto the surface cast and the silicone work stamp was placed on it. After UV-exposure under argon atmosphere, the work stamp was removed resulting in the imprinted sub-micro pattern.

To fabricate the 3D mold, the hybrid 3D-master (cast + microstructure pattern) is fixed in the middle of an open box made of Plexiglass sheets. The box is then filled with a two-component silicone mixture (Elastosil RT 620 A/B, *Wacker Chemie*) and dried for at least one day at room temperature. Finally, the 3D mold is cut into two pieces to remove the master. The 3D-mold for creating the test casts from polyurethane resin (R12GB, *Breddermann Kunstharze*) was fabricated in the same way.

For the fabrication of the final optical transparent component a two-component material system epoxy resin (E300GB, *Breddermann Kunstharze*) is blended. To inject the mixture into the 3D silicone mold, the material is taken up into a syringe. The filled mold is then put under pressure at 6 bars for 12 hours at room temperature to eliminate the formation of bubbles during preliminary curing. The final curing step is done in an oven at 40 °C for 24 hours at ambient pressure. It is important to note that this step is not real injection molding, neither is it material casting. Therefore, we define it as lab-scale injection molding.

Results and discussion

As a test case for the fabrication of a hybrid optics which combines micro- and (3D-) macro-sized features in one component, we decided to create a simple plane, square prism with a 1D diffraction grating on one of its surface. Figure 2 shows a 3D CAD sketch of the prism (A) and the 1D diffraction grating (B). The dimensions of the prism are $40 \times 40 \times 5\,mm^3$ and the grating comprises of 300 nm wide parallel lines with a pitch of 1 µm.

The active area of the grating is $1\,cm^2$ and is positioned in the middle of the prism.

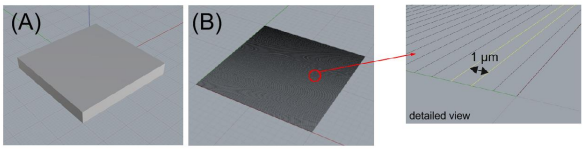

Figure 2: CAD model of a squared prism (A) and design of 1D diffraction grating (B).

Figure 3A shows the printed 3D object corresponding to the model of the prism. As seen, the surface is very rough in terms of the application in the field of optics. The surface roughness of the raw and the post treated printout was investigated with a contact profilometer (D150, *Veeco DEKTAK*) to quantify the improvement by the treatment. Figure 3 illustrates the 3D scans of an area of $2 \times 2\,mm^2$ of the raw (B) and the post treated (C) sample. Due to the layer-by-layer printing process the surface of the printed prism shows moderate undulations and a calculated arithmetic average roughness height (Ra) of about 5 µm. Figure 3C depicts the heavily improved surface after post-treatment. As can be seen, it was possible to reduce the waviness and therefore a Ra of 460 nm could be reached.

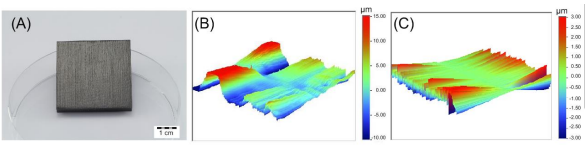

Figure 3: Printed 3D object corresponding to the model of the prism (A), 3D graphs of the measured profiles of the printed surface before (B) and after post-treatment (C).

For the structuring of the 1D diffraction grating, a two-inch Si-wafer was spin coated with a photoresist resulting in a resin thickness of 1 µm. First, a series of straight lines was written on a test sample to specify the optimal parameters for the laser writing and the photoresist post-process. During the test, the light dosage of each line was set by varying the laser-power or the scanning speed, resulting in the optimum parameters — 10 µW laser power at a scanning speed of $5\,mm\,s^{-1}$. The master of the diffraction grating was fabricated by using these parameters as shown in Figure 4A. It can clearly be seen from the microscope image of the PDMS work stamp, illustrated in Figure 4B, that the spacing between two adjacent lines is equidistant and corresponds to the designed pitch of 1 µm.

Figure 5A shows the fabricated 3D master with

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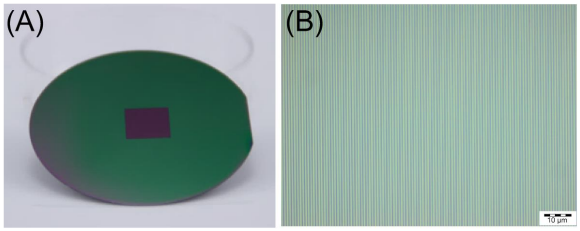

Figure 4: Photograph of a master with the written 1D diffraction grating (A) and microscope image of the grating of PDMS work stamp (B).

the integrated grating on the one side. As seen, the grating pattern was successfully transferred onto the surface cast in its centre. This master was used for fabricating the final optical hybrid component. Figure 5B shows the final optical component, which was fabricated using lab-scale injection molding.

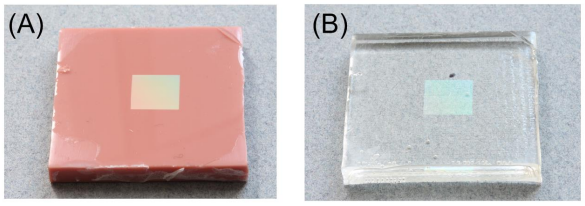

Figure 5: 3D master with the integrated diffraction grating (A) and the fabricated optical component (B).

Atomic force microscopy (AFM) was selected to determine the accuracy of the written 1D grating (master) and the final lab-scale injection molded optical component. Figure 6 depicts the comparison of the AFM images as well as the cross-sections of the master and the final optical component.

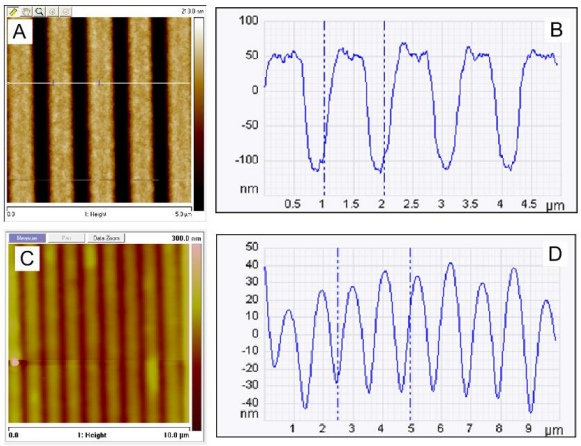

Figure 6: AFM images of the 1D grating (master) created by MALA (A) and its cross-section (B); the final optical prism (C) and its cross-section (D).

As seen in the upper part of the figure, the $5 \times 5\,\mu m$ scan of the master indicates the successful and highly accurate writing of the 1D diffraction grating with a structural depth of 150 nm, a width of approximately 300 nm at full width at half maximum of the depth and a pitch of 1 µm on the Si-wafer.

The $10 \times 10\,\mu m^2$ AFM scan of the final optical component offers the same pitch but a lower depth of about 50 nm. The decrease in depth of the lines is related to the shrinking effect, which occurs during UV-NIL and the molding step. A benefit of the UV-NIL process is that the photoresist defines the final surface quality. As a result, on the optically flat surface of the non-structured part of the component, a roughness Ra of about 3 nm was achieved. This offers another option to improve the surface quality which will be a part of our next work.

Conclusion & Outlook

In this preliminary study, we were able to show the proof-of-principle of a new method to fabricate a hybrid 3D optical plastic component, which combines (sub-) micrometer sized structures on a centimetre scale 3D macro object. The process chain of this “micro on macro” approach is based on four technologies. Firstly, additive manufacturing by 3D-printing was used, with which the bulk-optics are fabricated. The next step is the maskless direct laser write lithography to produce the (sub-) microscale optical structures, followed by UV-NIL to transfer the micro structures to the 3D-printed macro-optics. In the last step, lab-scale injection molding is used to fabricate the final optical component in a 3D silicone mold.

According to our proposed process chain we were able to fabricate a simple prism including a (sub-) microscale 1D diffraction grating on its surface and therefore we could demonstrate the abilities of the chain. The printout was not suitable for optical applications since its surface had a roughness of 460 nm after post-treatment. However, it could lead to improvements in the infrared range. The NIL step not only acts as a transfer process it also pushes the surface roughness of the whole hybrid device into a range suitable for optics. This result offers an improvement of the proposed process chain and will be part of our next publication.

Nevertheless, the combination of 3D-printing with UV-NIL enables the potential of a highly flexible

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and low cost production in the field of hybrid optical components. In our future work we will focus on the direct laser writing of continuous-relief (2.5D) microstructures on curved surfaces.

Acknowledgements

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References

[1] L. Li and A. Y. Yi, "Development of a 3D artificial compound eye", *Optics express*, Vol. **18**, No. **17**, August, (2010)

[2] J.-J. Kim, S. Chae, K.-H. Jeong, "Micropatterned single lens for wide-angle light-emitting diodes", *Optics letters*, Vol. **35**, No. **6**, March, (2010)

[3] M. T. Gale, M. Rossi, J. Pedersen, H. Schülz, "Fabrication of continuous-relief micro-optical elements by direct laser writing in photoresists", *Optical engineering*, Vol. **33** No. **11**, November (1994)

[4] L. Kuna, C. Leiner, W. Nemitz, F. Reil, P. Hartmann, F.-P. Wenzl, Ch. Sommer, "Optical design of freeform microoptical elements and their fabrication combining maskless laser direct write lithography and replication by imprinting", *Journal of Photonics for Energy*, Vol. **7**, Jan-Mar (2017)

[5] A. Lebib, Y. Chen, J. Bourneix, F. Carcenac, E. Cambril, L. Couraud, H. Launois, "Nanoimprint lithography for a large area pattern replication", *Microelectronic Engineering* **46**, (1999)

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Semi-Empirical Characterization of Freeform Microlens Arrays

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Abstract

Microlens arrays (MLA) are used since long for imaging and non-imaging applications. Thanks to their small dimensions they can be cost-effectively replicated onto flexible substrates, the final solution retaining a great deal of the substrate flexibility. Standard quasi-spherical microlenses can be realized using photolithography and subsequent self-assembled photoresist thermal reflow. Nevertheless, such microlenses fail to comply with stringent requests such as for example non-symmetrical beam shapes, which require more advanced non-symmetrical aka freeform microlens arrays (FMLA).

Despite being compatible with cost-effective replication processes, the manufacturing of FMLA molding tools conveys a rather high cost which all too often increases markedly with increasing tool area. In addition, it is rarely the case that the first design meets the specifications and often several design-fabrication-testing cycles are required thus pushing-up the cost beyond the reach of many Companies.

Unfortunately, the experimental characterization of small samples is normally unrealistic due to handling issues and experimental errors (e.g., alignments, output power, large source beam diameter, small detector aperture, etc.). Here, we demonstrate a method to overcome these limitations based on 3D surface sampling, computer generation of a ray-traceable model and ray-tracing performance simulation. The proposed approach is demonstrated for two commercially available microstructured optical foils.

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Introduction

In the last century, a wealth of opto-electronic devices spanning from lasers to photodiodes, image sensors, optical amplifiers, modulators, solar cells, light-emitting diodes, etc. has been developed which enabled a continuously growing number of applications in optoelectronics and photonics. Nowadays, all these devices contain a large palette of different optical elements such as lenses, diffusers, refractive and diffractive optical elements, etc. which are essential to their functionality and performance.

Moreover, the possibility to precisely control light propagation will enable many emerging technologies, including LI-FI, photonic sensors for automated driving (LIDAR) or optical sensors in Internet of Things applications. Still, as discussed recently [1], these applications and many more are in need of affordable optics with sufficient quality and available in large volumes and that can be integrated at device level. The trend for device miniaturization also raises a continuous need for optics and forces manufacturers to produce optical components with continuously reduced footprints and often improved performance and/or new functions.

Microoptics, defined as “the field of optics where optical components and systems are fabricated with microtechnologies” [2], facilitates the miniaturization and integration, enhances performance and reduces the manufacturing and packaging cost of many optical devices [3].

Precise micro fabrication technologies such as micro-milling and optical lithography have been developed which are today compatible with the production of micro-optical components. Interestingly, optical micro-structures are compatible with large-area replication [4] and hence offer substantial reductions in production costs, material usage and weight and make them compatible to large-area applications and not surprisingly, materials and replication processes technologies have been developed more or less in parallel.

The need for new integrated functionalities demands for optical elements with improved performance that pushed the limits of the design rules far beyond the classical microlens, microprisms and micropyramids towards new free-form micro-optical structures which offer customized light management possibilities in simpler configurations. Still, the complex shapes of these free-form optical microstructures and the required shape accuracy bear an enormous challenge for their fabrication [5], which, based on conventional fabrication processes, runs the risk of losing cost-effectiveness.

Axially symmetric microlenses (mainly spherical or slightly aspherical) can be realized using photolithography and subsequent self-assembled photoresist reflow thermal reflow [6][7]. Such micro-structures, although ideal for some applications, fail to comply with more stringent requests. For example, non-symmetrical beam shapes cannot be achieved efficiently due to skewness conservation [8] and demand non-symmetrical *aka* freeform (micro-) structures.

The recent developments in computer assisted design (CAD) and manufacturing technologies have led to the design and fabrication of freeform microlens arrays (FMLA) using for example direct writing [9][10], gray scale lithography [11] and more recently, additive manufacturing technologies such as two-photon polymerization [12] and ink-jet printing [13].

A common downside of all these technologies is the high cost of the master manufacturing, which increases largely with increasing area. In addition, it is rarely the case that the first design meets the specifications it was designed to meet and often several design-fabrication-testing cycles are required which is hardly affordable in many cases.

In the case of MLA or FMLA, the *unit cell* repeats itself thousands to millions of times throughout the complete surface making possible, in principle, to characterize a small sample with only a statistically relevant number of unit cells. When dealing with microstructures, sample areas as small as $1 \times 1\,\mathrm{m}^2$ contain several hundreds of such *unit cells*, a number that is statistically relevant for nearly all purposes.

Unfortunately, an accurate experimental characterization of such small samples is often impossible due to limited sample handling and experimental limitations such as source and detectors size and collection areas and alignment errors.

With the increase in computer power several optical simulation software packages are offered that can perform MonteCarlo ray-tracing through CAD-designed optical solids comprising

thousands of microstructures. For example, Optics Studio[1] LightTools[2] and SPEOS[3] are widely used by Industry and Academia. In these solutions, the user can establish ideal *experimental* conditions, i.e., with no restrictions on accuracy despite the characteristics of the tested component/s, source/s and detector/s.

On the other hand, metrology techniques such as stylus profilometry and white laser interferometry have since long been available to accurately record the profile of microstructured surfaces.

Unfortunately, the link between surface and optical simulation has proven somehow elusive with no software package being able (up to our best knowledge) to construct high-quality ray-traceable CAD models from experimentally recorded surface profiles.

However, we have found that this goal can be achieved combining several CAD software packages in the way described in the next sections.

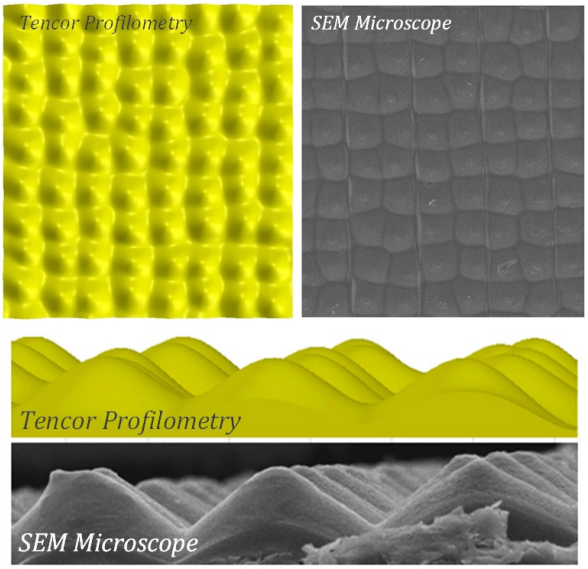

Figure 1: **BrightView GC-C90 de-glaring microstructures extracted from Tencor profilometry and observed under SEM. Top) top view. Bottom) Cross-section. Please note different parts of a GC-90 foil were used for each measurement.**

Description of the method

Our method comprises the following main steps:

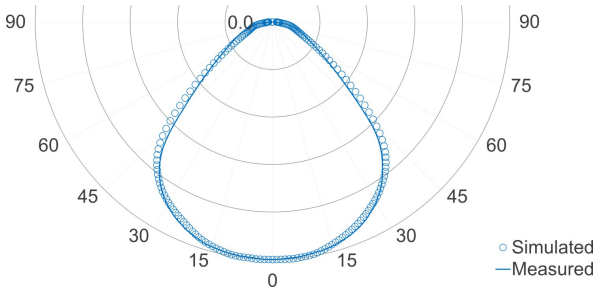

Figure 2: **Normalized luminance intensity distribution of a FL300 OLED lighting panel and a BrightView GC-C90 de-glaring foil in mechanical but no optical contact. The solid line represents the experimentally measured using a real GC-C90 foil and a Phillips FL300 white OLED) and open circles correspond to the theoretically predicted (ray tracing) response.**

- The surface profile is recorded as a XYZ point cloud.
- The recorded XYZ point cloud is converted in to an IGES[4] surface using *POINT CLOUD to NURBS* software[5] form RESURF with $10^3 \times 10^3$ control points.
- The IGES solid is open in Rhino5 3D software[6], the surface extruded up to a thin-film solid and the extruded solid finally exported as a parasolid.
- The parasolid model is opened in SolidWorks[7] and cut to the desired area and thickness and exported as Binary STL.[8]
- The STL solid is imported into the OpticsStudio ray-tracing software together with the relevant source and detector and the optical simulation performed.

For this work we selected two different commercial thin-film solutions namely BrightView G-GC90 de-glaring foil[9] and Luminit 60×30 asymmetric thin-film diffuser[10]. In both cases, the scanned area was $0.5 \times 0.5\,\text{mm}^2$ which contains a statistically relevant ensemble of microsructures. The scanned area of $0.5 \times 0.5\,\text{mm}^2$ corresponds to over 10^6 XYZ points.

Results

[1] http://customers.zemax.com/os/opticstudio
[2] https://www.synopsys.com/optical-solutions/lighttools.html
[3] https://www.optis-world.com/product-offering-light-simulation-virtual-reality-software/SPEOS
[4] Initial Graphics Exchange Specification
[5] http://www.resurf3d.com/Pointcloud2Nurbs.htm
[6] https://www.rhino3d.com/de/
[7] http://www.solidworks.de/
[8] Stereolithography
[9] http://www.brightviewtechnologies.com/
[10] http://www.luminitco.com/

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BrightView GC-C90 de-glaring foil

The generated ray-traceable CAD model of the BrightView GC-C90 is shown in Figure 1 together with a SEM picture[11] where the excellent agreement is evident.[12][13]

Their de-glaring characteristics were simulated using OpticStudio software using 10^6 rays. In this simulation the model was located in close proximity (0.01 mm) to a Lambertian white source of the same size (which simulates an OLED source — see below) and the intensity distribution across a polar detector recorded.

For comparison, a real $110 \times 110\,\mathrm{mm}^2$ GC-C90 de-glaring foil was set into physical contact with a commercially available OLED lighting module.[14] The OLED-foil combination was mounted on a gonio-spectrophotometer and the complete system accurately aligned. The OLED was the rotated around its center and the luminance recorded every 1*o*.

The simulation and experimentally recorded luminance intensity distributions, shown in Figure 2, confirm the excellent agreement between the real and the CAD model. Noteworthy, the simulation took about ten times shorter.

Luminit 60 × 30 asymmetric diffuser

In order to extend our study to highly asymmetric, i.e., freeform, microstrutures a similar comparison was performed using the Luminit 60 × 30 asymmetric diffuser. The generated solid, presented in Figure3 was also in excellent agreement with the profile determined using SEM (not shown).

The radiant intensity of the CAD model upon normal illumination with a perfectly collimated green source (λ = 550 nm) was simulated using a) the measured BSDF[15] data provided by Luminit.[16] and b) the built CAD model.

[11] Scanning Electron Microscopy
[12] Please note that we use different parts of the same foil for each measurement
[13] The scanning area is roughly $0.5 \times 0.5\,\mathrm{mm}^2$
[14] LF300 white OLED from Philips
[15] Bi-directional Scattering Distribution Function
[16] `https://www.luminitco.com/sites/default/files/downloads/dll`

The comparison is shown in 4 where it can be seen that, as in the GC-C90 case, an excellent agreement was found between experimentally measured and simulated characteristics.

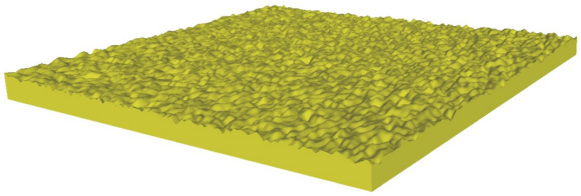

Figure 3: Luminit 60 × 30 ray-traceable CAD solid created from the measured surface profile.

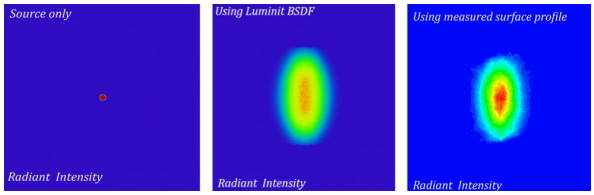

Figure 4: predicted radiant intensity of the light source itself (left) and after illuminating a CAD model of the Luminit 60 × 30 diffuser (centre). The radiant intensity predicted using the experimentally measured BSDF is shown on the right.

Conclusions

Optical microstructures are widely used for a plethora of opto-electronic devices. While historically limited to spherical microlenses, recent advances in computing and fabrication microtechnologies have broaden the options to incorporate more complex forms like aspherical or even asymmetric freeform.

Among the many advantages offered by optical microstructures their compatibility with roll-based cost-effective manufacturing process is especially interesting for mass-market applications. Despite this, the affordable origination (time- and cost-wise) is still limited to relatively small areas ($\sim 1\,\mathrm{mm}^2$) which are difficult to characterize.

CSEM has demonstrated that using existing metrology equipment and CAD software packages the characterization effort that must be committed to the characterization of such optical solutions can be extremely reduced while ensuring a high accuracy. On the other hand, access to ray-traceable CAD models facilitates the study of, e.g., alignment tolerances thus speeding up not only the design and fabrication but also the integration phases. Moreover, once the CAD model is constructed, its response can

be estimated in a wide number of configurations with nearly no additional effort.

Unfortunately, several CAD software packages are currently needed to build such ray-traceable CAD models from experimentally measured surface profiles. It is strongly desirable to have a single CAD software package able to make the complete process described here.

Acknowledgment

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References

[1] S. Bäumer, A. Yi, Topical issue on plastic optics, Adv. Opt. Techn. 5(4), p. 275–276 (2016)

[2] S. Sinzinger, R. Kleindienst (2011), Microoptics and freeform optical beam shaping, Part of H. Landolt and R. Börnstein, Group VIII Advanced Materials and Technologies (Numerical Data and Functional Relationships in Science and Technology), Vol 3. Springer, Berlin, Heidelberg

[3] R. Voelkel, Wafer-scale micro-optics fabrication, Adv. Opt. Techn., 1, pp. 135–150 (2012)

[4] L. Kuna; C. Leiner; W. Nemitz; F. Reil; P. Hartmann; F.P. Wenzl; C. Sommer, Optical design of freeform micro-optical elements and their fabrication combining maskless laser direct write lithography and repli-cation by imprinting, J. Photon. Energy. 7, 016002 (2017)

[5] F.Z. Fang, X.D. Zhang, A. Weckenmann, G.X. Zhang, C. Evans, Manufacturing and measurement of freeform optics, CIRP Ann.Manuf. Techn. 62, p. 823–846 (2013)

[6] P. Nussbaum, R. Völkel, H.P. Herzig, M. Eisner and S. Haselbeck, Design, fabrication and testing of microlens arrays for sensors and microsystems, J. Pure and Applied Optics 6 (6) p.617 (1997)

[7] D. Daly, R.F. Stevens, M.C.Hutley and N. Davies, The manufacture of microlenses by melting photoresist. Measurement Science and Technology 1, (8) p. 759 (1990)

[8] L. Sun, S. Jin, and S. Cen, Free-form microlens for illumination applications, Appl. Opt. vol 48, 5520–5527 (2009)

[9] F. Burmeister. S. Steenhusen, R. Houbertz, U.D. Zeitner, S. Nolte, A. Tünnermann, Materials and technologies for fabrication of three-dimensional microstructures with sub-100 nm feature sizes by two-photon polymerization, Journal of Laser Applications 24 (4) p. 04014 (2012)

[10] K. Naessens, H. Ottevaere, R. Baets, P. Van Daele, and H. Thienpont, Direct writing of microlenses in polycarbonate with excimer laser ablation, Appl. Opt. 42, 6349–6359 (2003)

[11] Q.Deng, Y. Yang, H.Gao, Y. Zhou, Y. He and S. Hu, Fabrication of Micro-Optics Elements with Arbitrary Surface Profiles Based on One-Step Maskless Grayscale Lithography, Micromachines 8(10), 314 (2017)

[12] http://additivemanufacturing.com/2017/01/24/nanoscribe-additive-manufacturing-of-micro-optics/

[13] G. Basset, A. Luu-Dinh, C. Schneider, F. Herzog, F. Zanella, A. Mustaccio, Advanced Microlenses Fabrication Techniques, CSEM Scientific and Technical Report 2016 p. 69. Available online: https://www.csem.ch/Doc.aspx?id=44148

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The T-Word: Tolerancing, and its Role in Illumination Optics Design

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Abstract

Tolerancing is a subject that is often overlooked, or not fully addressed, in the design of illumination optics. Tolerancing methods are well developed and understood in the lens design and imaging system design fields, but tolerancing of illumination optics is much less well developed. Optical design and optimization software tools can allow the designer to make new and exciting designs, but it is possible that the design may not be economical to manufacture due to the sensitivity of the design to variations in the manufacturing process. New tolerance analysis tools in optical design and analysis software allows designers and engineers to evaluate the effect of manufacturing variations and how it will affect the overall performance of the system. This makes it possible to see if a design is truly practical and economical. We will look at the tolerancing methodology as well as some tolerancing examples in this paper.

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Introduction

One definition of tolerance in the Merriam-Webster online dictionary is: the allowable deviation from a standard; especially: the range of variation permitted in maintaining a specified dimension in machining a piece. In optical and illumination design this is used to define how much a manufactured design can deviate from the optimized or “perfect” design and still deliver an acceptable level of performance. An optical designer will realize that the part that is produced based on their design may not fully match the original design. A tolerant design is one that will still perform within a given range despite these inevitable differences due to manufacturing.

Many computer based optical design and analysis programs feature powerful optimization tools that optical engineers and designers can use to design complex and high performance components and systems for lighting and illumination applications. In some cases, these designs may not translate well to a production environment. Figure 1 shows an optimized luminaire reflector that would be difficult to produce accurately and consistently. Fortunately, some of these same software tools can also allow the capability to check the tolerance of a design to see if changes to the original design need to be made.

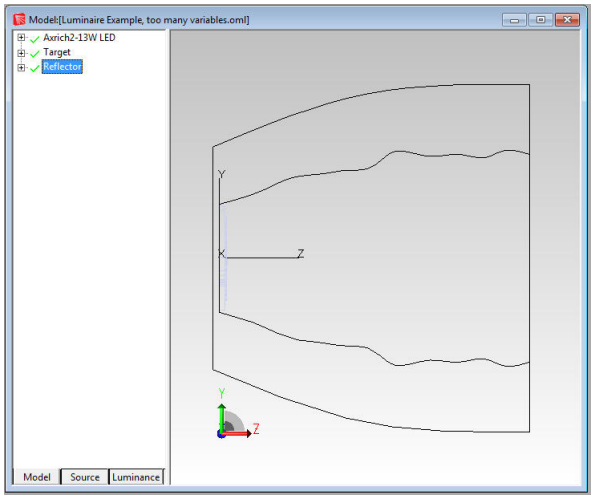

Figure 1: Reflector with complex shape.

Tolerancing in Optical Systems

Tolerance analysis in lens and imaging system design is a well-established and understood field. Optical design programs such as OSLO, CodeV, and others, feature robust tolerancing routines. The initial tolerance data in OSLO for example is based on the default manufacturing tolerances outlined in the ISO 10110 drawing standard. Users are then able to change this initial tolerance data by referencing the correct class of data: Surface Tolerance Data, Component Tolerance Data, and the User-Defined-Group Tolerance Data [1]. The user can then select the tolerance method to use. The methods available may include, Monte Carlo analysis, Hopkins-Tiziani-Rimmer (HTR) method, user-defined tolerance, computer change table, and distributed change methods.

Tolerancing in Illumination Systems

Tolerance analysis in illumination design is a much newer and less developed process. The goal of the process is the same though, to perturb the initial design in a systematic way and analyze the effect of these changes on the system’s performance. The performance metrics can include, flux, illuminance values, illumination patterns, uniformity, beam width, candela values, intensity patterns, luminance, and color coordinates. When an illumination system tolerance analysis is to be performed, the first step is to identify the parameters in the design that can change during the manufacturing process. These parameters can include curvature, aspheric terms or deviation from a spherical surface, dimensional changes, changes in conic curvatures and conic constants, misalignment of sources such as LEDs, variations in source output, changes in surface finish, and other changes in material and/or surface properties.

Once the parameters that can change have been identified and defined, the next step is to determine by how much these parameters can change. This information may come from past experience, discussions with vendors, sample measurement, and/or experimentation. In many cases it may be a combination of several sources of information. After the range of parameter variation is determined, the method for choosing values within that range during the tolerancing process can be selected. Options can include Normal or Gaussian, Uniform, or End Point analysis. The Normal or Gaussian method will distribute the values in a Gaussian distribution centered on the nominal value with the high and low limits of the parameters as the limits for the

Gaussian curve. A Uniform distribution will evenly spread the values across the range of the parameter value. An End Point analysis will test the high and low values for the parameter.

The Gaussian or Uniform options can be used to scan through a range of values for a parameter. For example, if the radius of curvature of a surface for a TIR hybrid lens can vary by +/- 1 mm. the Gaussian or Uniform options will allow the user to scan through values in the range. The End Point option can be useful to scan the maximum and minimum range of the parameter values to see the range of the performance change in the design. This can be a good option when there are numerous parameters to evaluate. After an initial analysis is used to identify the most troublesome parameters, additional analysis can also be run using more trials or a different method such as Normal/Gaussian or Uniform.

The Monte Carlo method can be used in illumination optics tolerancing. The Monte Carlo method uses random numbers to generate a sequence of optical elements, such as reflectors or lenses, determined by the upper and lower limits defined by the user. Each random iteration defines a new version of the optical element. This method allows all of the parameters to be varied or perturbed simultaneously, greatly speeding up the tolerancing process.[2]

Setting up a Tolerance Analysis

The tolerance analysis process can be broken down into a series of steps.

- Identify the parameters that are to be varied or changed during the tolerance analysis
- Determine the range of motion or limits for those parameters
- Select the method for varying the parameters
- Choose the number of iterations to run. More iterations will generally result in a more accurate representation of the results.
- Run the tolerance analysis
- Analyze the results and make changes/corrections to the design if necessary

Illumination System Tolerancing Examples

Example 1: Reflector Tolerance

This example will show a tolerance analysis of a reflector used in a LED luminaire. The reflector has been optimized to produce an even illumination pattern in the central region of a target. Figure 2 shows the optimized design and illumination pattern.

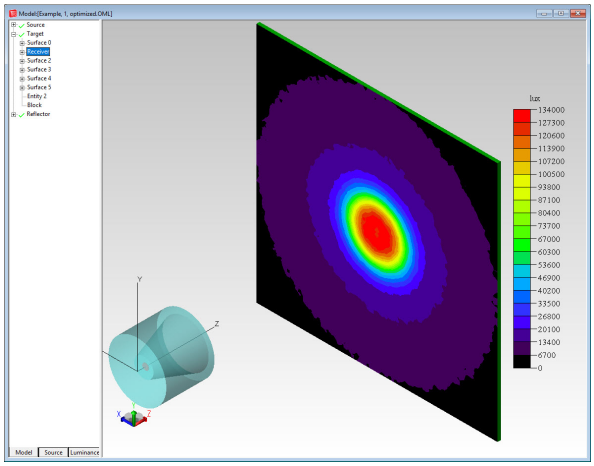

Figure 2: Optimized reflector and illumination pattern.

In this example the end point of the reflector curve will be allowed to move. This variation could be the result of spring back or movement of the end of the reflector after it is molded or spun. The range of motion for this point is +/- 1 mm horizontally. Figure 3 shows the point that can move during the tolerance analysis and its range of motion.

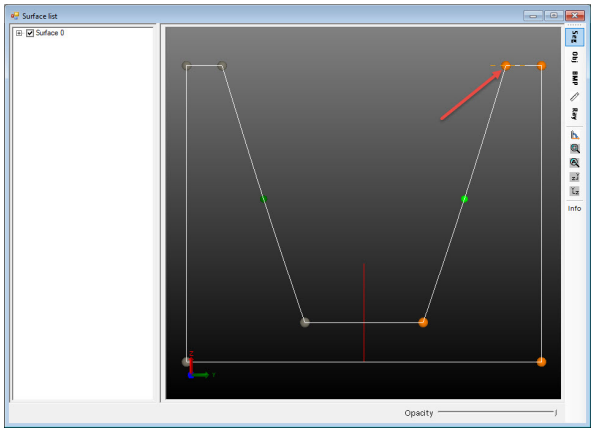

Figure 3: Reflector profile and point that can move +/- 1 mm.

The number of iterations for the tolerance analysis was set to 250 and the distribution method was Gaussian. Figure 4 shows the results of the

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tolerance analysis with the error along the X-axis and the accumulated ratio in percentage along the Y-axis. As can be seen, most of the results are on the left side of the plot with the lowest error function. This design should be fairly tolerant of changes due to manufacturing variations.

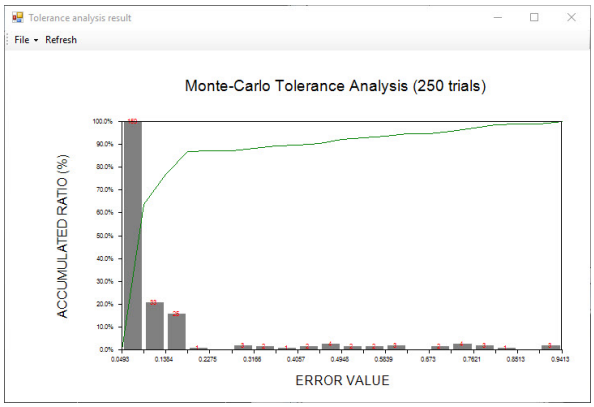

Figure 4: Accumulated error values for 250 iterations.

Figure 5 shows the Error Value plotted as a function of the Variable Value. The variable value for the optimized condition was 7.178 mm. The variable values for the best and worst-case conditions were 7.180 mm and 6.180 mm respectively. Figures 6 and 7 show the illumination patterns for the best and worst-case conditions respectively.

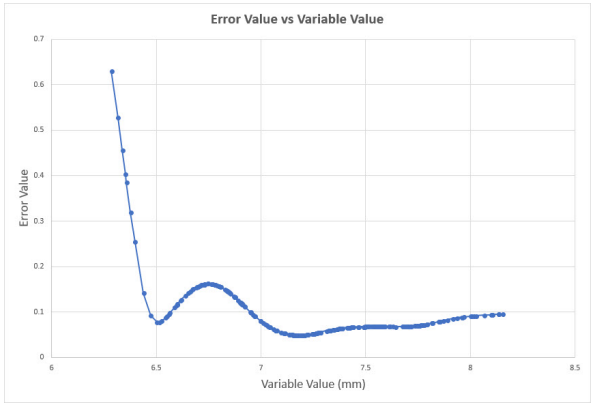

Figure 5: Error Value vs Variable Value.

Example 2: LED TIR hybrid lens tolerance

This example will show a tolerance analysis of a LED TIR (total internal reflection) hybrid lens. A TIR hybrid lens uses a combination of total internal reflection and refraction to produce a desired illumination or beam pattern. The TIR hybrid lens in this example has been optimized to produce a 2.5-degree half angle beam. Figure 8 shows the initial design and candela, or intensity, plot.

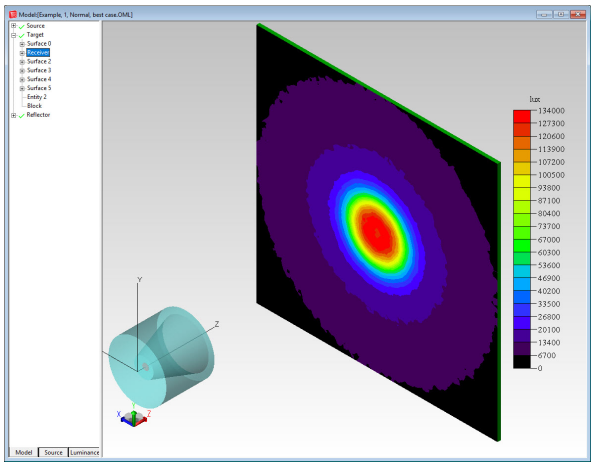

Figure 6: Best-case illumination pattern.

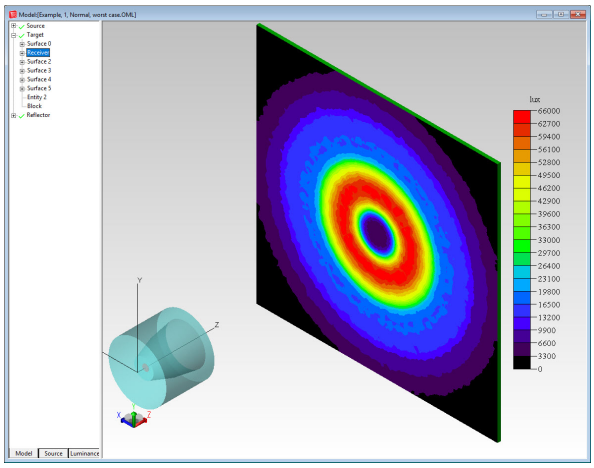

Figure 7: Worst-case illumination pattern.

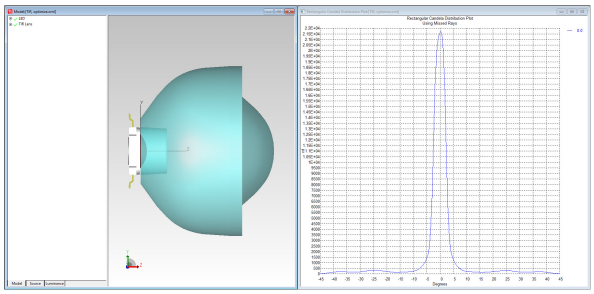

Figure 8: Optimized TIR hybrid lens and intensity plot.

In this example the spline control point on the TIR portion of the lens will be allowed to move. This variation could be the result of molding or machining differences during the manufacturing process. The range of motion for this point is +/- 1 mm horizontally and vertically. Figure 9 shows the point that can move during the tolerance analysis and the range of motion.

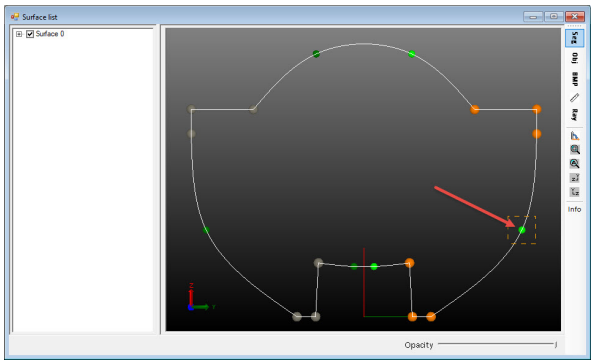

Figure 9: Lens profile and spline control point that can move +/- 1 mm.

The number of iterations for the tolerance analysis was set to 250 and the distribution method was Gaussian. Figure 10 shows the results of the tolerance analysis with the error along the X-axis and the accumulated ratio in percentage along the Y-axis. As can be seen, the results are more spread out than the previous example, but in this case the error value does not vary by a large amount. This design should also be fairly tolerant of changes due to manufacturing variations.

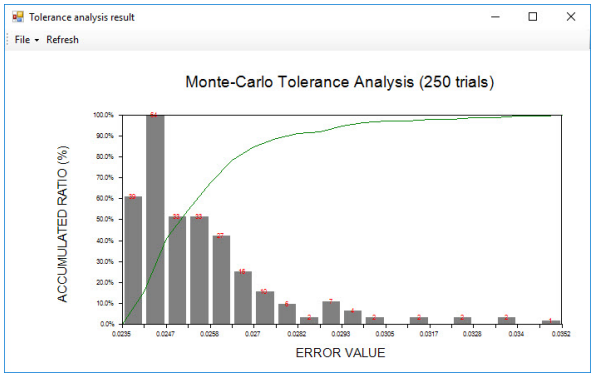

Figure 10: Accumulated error values for 250 iterations.

The variable values for the optimized condition were 10.586 mm and 6.595 mm. Figures 11 and 12 show the intensity patterns for the best and worst-case conditions respectively. The variable values for the best case and worst-case examples were (12.211 mm, 5.515 mm) and (11.123 mm, 5.635 mm) respectively.

Example 3: LED TIR lens LED position tolerance

This example will show the position tolerance of an LED and a TIR hybrid lens. The position of the LED relative to the optimized position is changed to check how variations in spatial relationship between the lens and the LED due to assembly

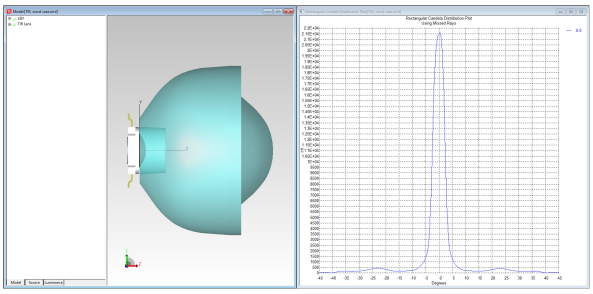

Figure 11: Best-case intensity pattern.

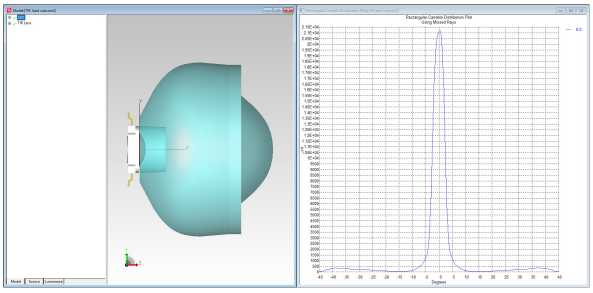

Figure 12: Worst-case intensity pattern.

tolerances effect the performance parameters of the system. Figure 13 shows the system and the candela plot for the nominal LED position.

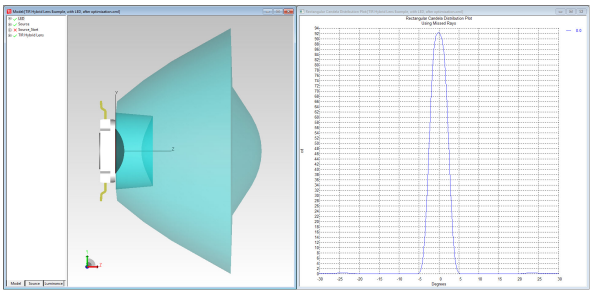

Figure 13: Optimized LED position with TIR hybrid lens.

In this example the position of the LED will be allowed to move in 3 dimensions, X, Y, and Z. This could be the result of variations in the assembly process. The range of motion for the LED is +/- 0.5 mm along the X, Y, and Z axes. For this analysis we will assume that there are no rotational variations, though in reality this would probably not be the case. These parameters could easily be added to the analysis.

The number of iterations for the tolerance analysis was set to 250 and the distribution method was Gaussian, as in the previous examples. Figure 14 shows the results of the tolerance analysis with the error along the X-axis and the accumulated ratio in percentage along the Y-axis. The results are spread across the plot, though in this case it should be noted that the best-case result had an

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error function of 0.0013804 and the worst-case result of 0.2868755, a ratio of 208:1. Figure 15 shows a plot of the error values for all 250 iterations. This design will be sensitive to LED alignment if it is desired to maintain the best performance.

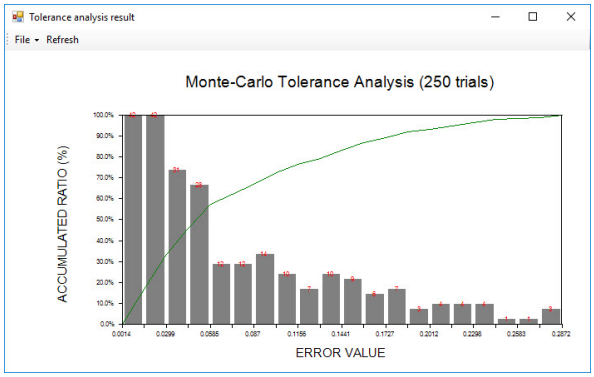

Figure 14: Accumulated error values for 250 iterations.

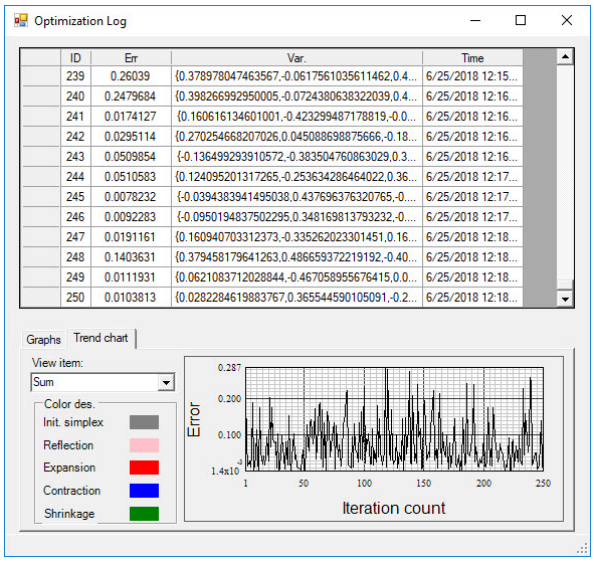

Figure 15: Error values for all 250 iterations.

Figures 16 and 17 show the intensity patterns for the best and worst-case conditions respectively. The variable values for the best case and worst-case examples were (0.010 mm, –0.0392 mm, –0.0885 mm) and (–0.4644 mm, 0.001 26 mm, 0.466 96 mm) respectively. Note that the intensity of the worst-case is about one-half that of the best-case solution, 48 cd vs. 91.5 cd. Also note the asymmetry in the beam pattern.

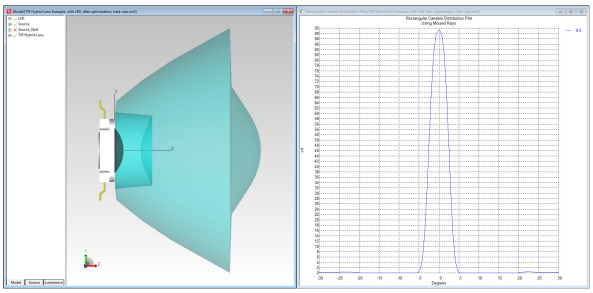

Figure 16: Best-case intensity pattern.

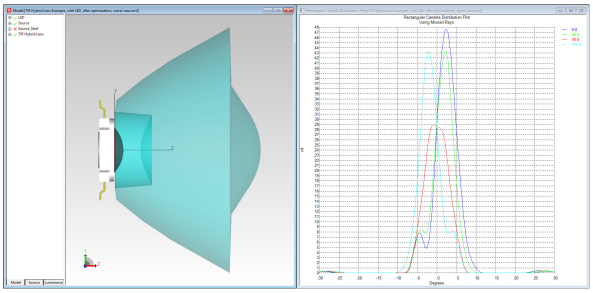

Figure 17: Worst-case intensity pattern.

Conclusions

The tolerance of a luminaire design can play a large role in whether the design can be effectively translated into a production environment. If a design is too sensitive to manufacturing variations, meeting the design goal of the luminaire may be costlier than expected, or it may not be feasible to manufacture. A tolerance analysis is a great tool to determine the tolerance or sensitivity of the design. Computer aided tools allow for this process to be simplified and automated. In this paper we have discussed the background and methodology of the process. We have also shown examples of the tolerance analysis process and the results showing the effect on the performance of the system due to the variations.

Acknowledgment

The author would like to thank his colleagues at Lambda Research Corporation for their assistance in this paper. The author would also like to thank the organizers of the LED Professional Symposium for their hard work in setting up this event.

References

[1] OSLO Program Reference, Lambda Research Corporation

[2] Lambda Research Corporation webinar “Monte Carlo Tolerancing in TracePro”, January 2018

Multi-Functional Optical Silicone-to-Thermoplastic Over-Molded Component for LED Lighting

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Abstract

Silicone optics have become quite well adopted in high end LED lamps & luminaires lighting applications, such as, e.g., automotive headlamps, outdoor streets, roadways and stadium as well as retails. Dow Performance Silicones (formerly Dow Corning) and Gaggione have largely contributed by demonstrating the benefits of silicones optics from various perspectives, such as, e.g., resistance to high heat and lumen fluxes, stability against UV radiation, high resistance against scratch and impact, good compression set, enhanced optics and free form lenses design capabilities [1] [2], and opportunities to optimize manufacturing processes of optics at large volume industrial scales.

However, an area that was less explored until now was the possibilities to combine benefits of both thermoplastics and silicones in the design of optics for applications in LED lighting. Although over-molding of non optical Liquid-Silicone-Rubber (LSR) on thermoplastics and composites, glass or metallic substrates is not new [3], Dow Performance Silicones and Gaggione have decided to bring forward this technology to the world of optics for LED lamps and luminaires.

The integration of silicone optics with thermoplastics enables multiple functionalities to be brought into a single component with optimal performances. These functionalities include high grades optics (including accurate surface features), ingress protection (IP), impact protection (IK), rigidity or flexibility, toughness, dimensional stability, scratch resistance and ease of assembling into LED lighting modules for the luminaire manufacturers.

The work presented here will describe how chemical adhesion of optical moldable silicones can be developed to a thermoplastic substrate. The silicone is over-molded on thermoplastics such as polycarbonate (PC) or polybutylenetherephtalate (PBT). The chemical adhesion is made via an intermediate silicone coupling layer that is not impairing the optical function of the assembly. Various scenarios have been considered, which take into account variables and constraints dictated by both the injection molding processing (for the over-molding steps), and the mode of deposition of the intermediate silicone adhesive layer. The effect of thermoplastic pretreatment, such as UV or plasma, will also be discussed. This will be put into context with respect to their effects on adherence strength between the silicone optics and the thermoplastic substrates, as well as their effects on surface chemistry and roughness.

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Introduction

In the 1960s Dow started the development of optical silicones for a wide range of applications, which included light guides for early lasers, contact lenses, and optical adhesive for displays [4]. In the early 2000s Dow leveraged this further to develop and commercialize silicone encapsulants for Light Emitting Diodes (LED) used for illumination purposes [5]. This silicone encapsulants development helped foster the LED lighting revolution of the last two decades, leading to the global enthusiasm for energy efficient lighting that can be achieved with LEDs, displacing incandescent and halogen lighting.

Since 2011, Dow has been developing the market of silicone optics with various grades of DOWSIL™ Moldable Optical Silicones materials, specifically designed for the benefits of applications in LED lighting, such as, e.g., automotive headlamps, outdoor street and roadway lighting, architectural and stadium lighting or retail lighting [2], [6] to [10].

DOWSIL™ Moldable Optical Silicones materials are chosen for the following key benefits:

- Ease of fabrication of complex shapes, including negative draft angle, by industrial injection molding processes [1] [2] [7].
- High transparency, down to UV-C wavelengths below 300 nm [6].
- High resistance against heat and environmental aging (non-yellowing) [1].
- Lighter than glass or quartz [1].
- Rubbery properties enabling the optical envelope (or enclosure of the LED module) to also provide efficient sealing performances against water and dirt ingress in light engine used outdoor [8].

In a recent case study [9], Schreder have implemented the integration of a grape of TIR lenses (made of DOWSIL™ MS-1002) into a plastic holder for further assembly into an LED module, as illustrated in figure 1. Schreder have selected silicone optics for their benefits in terms of resistance against high heat and high lumen flux, as well as excellent optical performances (high transparency, low haze). In the present case, the eight silicone collimators of each grape are mechanically integrated into a plastic lens holder, which enables them to fix and align the optics against the LED-PCB.

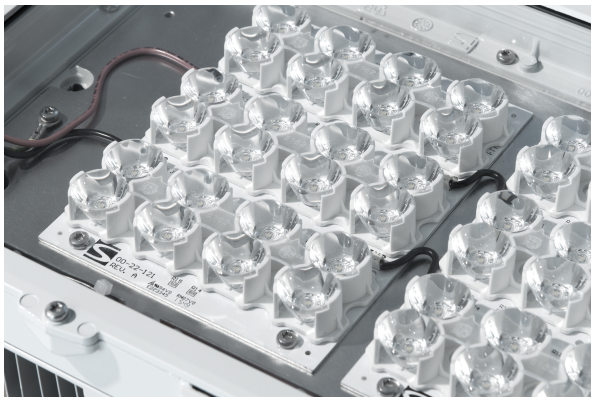


Figure 1: Grapes of eight individual collimators attached together made of DOWSIL™ MS-1002 Moldable Silicone, snapped into a plastic holder for assembly into Schreder OMNIblast™ LED module [9].

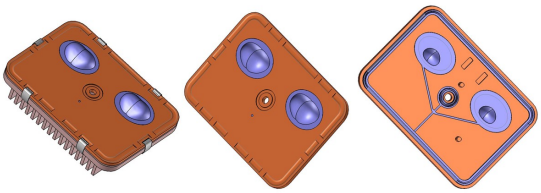
Results and discussions

The results that will be discussed in the present study are in a development stage and are subject to further validation at the industrial scale. The purpose is to demonstrate the feasibility of effectively integrating silicone optics onto rigid substrates, such as thermoplastics, metals or glass. This combines the benefits of these rigid substrates with the benefits of moldable optical silicone, in terms of design (negative draft angles), mechanical (scratch and impact resistance), optical performance and durability under typical LED lighting operating conditions.

Silicone optics over-molding to plastic insert

In order to bring even more functionalities to the optical plate, the next logical step was to consider over-molding the optical silicone lens onto the plastic plate. This includes over-molding of the surrounding sealing ring on the periphery of the plate as illustrated by the drawing on the right in figure 2.

The over-molded silicone optic onto its thermoplastic insert (middle drawing in figure 2) then constitutes the enclosure of the LED-PCB after fixation to the heat sink on the back side, as illustrated by the drawing on the left in figure 2. It is necessary that the optical grade silicone used for the optics function adheres to the plastic insert. This is to ensure that the LED module will be well protected against water and dirt ingress, i.e., reaching IP66 to IP69 ratings. We have therefore developed an over-molding process that



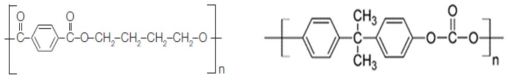


Figure 2: 3D drawing of silicone lenses over molded onto thermoplastic insert for assembly onto LED module (PCB and heat sink).

Figure 4: Polybutylene terephthalate (PBT, left) and Polycarbonate (PC, right) chemical structures.

includes a pre-treatment of the thermoplastic insert. This offers a surface that is chemically compatible and reactive with the moldable optical silicone. Pictures shown in figure 3 illustrate the LED lighting module that was realized at this point in time for demonstrating the feasibility to over-molding DOWSIL™ MS-1002 on PBT-30GF composite insert.

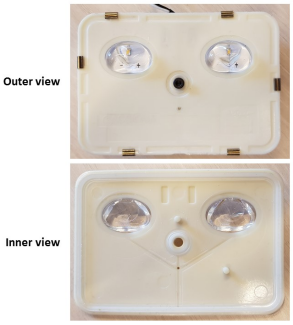


Figure 3: Pictures of the LED module prototype. DOWSIL™ MS-1002 overmolded onto PBT-30GF, with an optical coupling layer for developing chemical anchorage between MS-1002 and PBT.

Surface characteristics of thermoplastics

The two grades of thermoplastics used in this study are BASF Ultradur 4300-G6 PBT and COVESTRO Makrolon AL2447 PC. Ultradur 4300-G6 is an easy flowing injection molding PBT reinforced with 30% glass fiber (PBT-30GF) for obtaining a rigid, tough, and dimensionally stable parts. The chemical structures of these two polymers are shown in figure 4.

X-ray photoelectron spectroscopy (XPS) was used to analyze the surface chemistry of these thermoplastics after injection molding the plastics inserts, prior to being over-molded with DOWSIL™ MS-1002 moldable optical silicone.

With the exception of adventitious surface contamination, the elemental composition of the PBT and the PC surfaces are showing ca. 85 percents carbon and 15% oxygen. This ratio of elements is expected from the structure of the polycarbonate (shown in figure 4). However, it would be expected that PBT would have 75% carbon and 25% oxygen. This indicates that there has been surface segregation of material to the surface of the PBT during injection molding of the plastic insert. This can be seen clearly when looking at the carbons spectra acquired from the molded PBT surface and comparing it to the carbon 1s spectrum of a cleaned standard of the same grade of PBT (see figure 5). Of most significance is the absence of the pi-pi* shake up satellite peak in the spectrum from the molded PBT, which is representative of the aromatic group. The absence of the pi-pi* shake up satellite indicates that the segregation of material is overlaying the surface of the PBT. An over-layer of material on the surface could have a negative impact on adhesion.

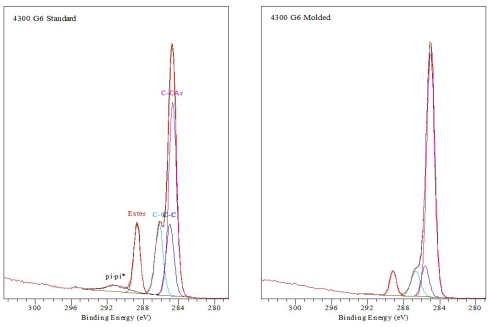


Figure 5: Carbon 1s spectra acquired from the surface of the molded PBT (right) compared to a spectrum acquired from the surface of a standard of the same grade PBT (left).

After atmospheric plasma treatment of the PBT and PC substrates, we observed an increase in oxygen content at the surfaces of these two plastics: ca. 68% carbon and 30% oxygen for

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PBT, and ca. 70% carbon and 25% oxygen for PC. In both cases, the plasma treatment was also introducing ca. 1% nitrogen on the surface, which is consistent with a plasma treatment applied under atmospheric ambient air conditions. An example of a carbon 1s spectrum acquired from the surface of the molded PBT after plasma treatment is shown in figure 6. The pi-pi* shake-up satellite peak is now clearly observed, which indicates that the plasma treatment has had a cleaning effect in the removal of the segregated material. It can also be seen that additional peaks were fitted to the spectrum to account for new functional groups being present at the surface. These peaks represent carboxylic acid, carbonyl, and hydroxyl functional groups. This would indicate that there has been some polymer chain scission in the PBT structure around the ester linkage.

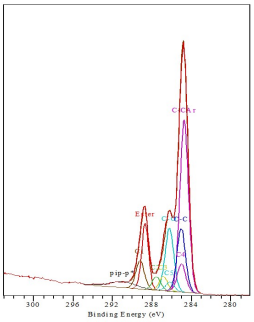

Figure 6: Carbon 1s spectrum acquired from the surface of the molded PBT after plasma treatment.

To understand the impact of plasma treatment on the surface of the PC a comparison of carbon 1s spectra acquired from the PC before and after plasma treatment is shown in figure 7. The carbon 1s spectrum acquired from the PC before plasma treatment is as expected from the chemical structure shown in figure 4. Additional peaks had to be fitted to the carbon 1s spectra acquired from the plasma treated surface. This is consistent with the increase in percentage oxygen detected at the surface. This additional peak indicate that carboxylic acid, ester, carbonyl and hydroxyl functional groups are now present at the surface of the PC after plasma treatment. These results indicate that the plasma treatment has an impact in both removing a weak boundary layer and introducing functional groups that will aid spreading and chemical adhesion of the silicone coupling layer applied prior over-molding of DOWSIL MS-1002 moldable optical silicone.

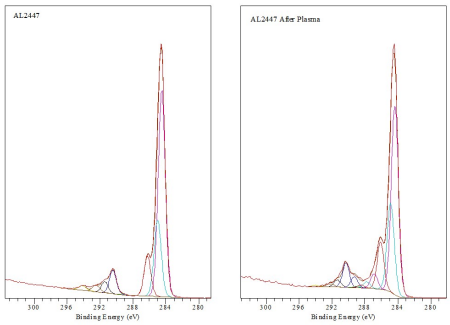

Figure 7: Carbon 1s spectra acquired from the surface of the molded PC before (left) and after plasma treatment (right).

Silicone coupling layer

To ensure chemical anchorage is developed between the moldable optical silicone and the thermoplastic substrates, we developed two solutions; (a) an optical silicone coupling layer and (b) a selective adhesion liquid silicone rubber coupling layer. Both coupling layer solutions have been formulated in order to develop chemical coupling between the moldable optical silicone and the substrates considered.

On one hand, the optical silicone coupling layer can be applied to the substrate by spraying, brushing or possibly dip coating prior drying and over-molding with the moldable optical silicone.

On the other hand, the selective adhesion liquid silicone rubber can be applied by a first step injection molding process onto the plastic substrate, followed by a second step over-molding with the moldable optical silicone. The process of over-molding DOWSIL MS-1002 moldable optical silicone on a non optical LSR is already well understood and controlled for application in LED lighting, such as with SoundOff Signal emergency vehicle outdoor lighting [10]b.

The best approaches for over-molding DOWSIL MS-1002 moldable optical silicone onto a plastic are being pursued and optimized now in the scope of industrial development jointly held by Dow Performance Silicone and Gaggione in order to bring commercially viable injection over-molding process solutions to the market of LED lighting lamps and luminaires.

Conclusions

The work described here and presented today is part of an ongoing development aiming at bringing

industrially and commercially viable solutions of silicone optics integrated with thermoplastics substrates, either non-optical (PBT) or optical (PC). During the talk at LPS'2018, the various approaches considered for the coupling layer and over-molding processes will be further discussed within the light of results obtained at that point of time. The ultimate purpose is to provide the LED lamps and luminaires industry additional options for over-molding an optical silicone lens onto a plastic, metal of glass substrate. The hybrid optic obtained can then be easily integrated into a light engine for applications in professional retail lighting [7], outdoor street [8] and stadium [9] lighting, and automotive lighting [10].

Acknowledgment

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References

[1] (a) F. de Buyl, M. Beukema, K. Van Tiggelen, K. W. Rong, N. L. Rankey, J. Steinbrecher, "Dow Corning® Moldable Silicone Leading Innovations in LED Light Fixtures", Journal of The Society of Silicone Chemistry, Japan, issue 131, pp. 23-38 (2014).
(b) H. Ferreira da Silva, "Moldable Optical Silicones enable LED lamps and luminaire designs", LEDs Magazine, (Oct 2012).

[2] F. de Buyl, M. Beukema, K. Van Tiggelen, "Why Moldable Silicone is Driving Innovation in Engineering of LED Optics for Professional Lighting?" Proceeding of LPS'2015 conference, Luger Research Ed., pp178-187 (2015).

[3] (a) E. Haberstroh, C. Lettowsky, "Multi-component injection moulding of liquid silicone rubber/thermoplastic combinations", Journal of Polymer Engineering, vol.24(1-3), pp203-214, (2004).
(b) E. Haberstroh, C. Ronnewinkel "LSR thermoplastic combination parts in two-component injection molding", Journal of Polymer Engineering, vol.21(2-3), pp303-318, (2001).

[4] (a) M. E. Nelson, M. E. Nelson, "Organosiloxane encapsulating resins", Patent Application US 3,284,406 (1966).
(b) E. L. Kern, "Laser communication system using flexible silicone transmission line", Patent Application US 3,434,776 (1969).
(c) K. E. Polmanteer, "Optical compositions of silicone rubber, Patent Application" US 3,518,324 (1970).
(d) D. D. Mitchell, "Wettable silicone resin optical devices and curable compositions thereof", Patent Application US 4,487,905 (1985).

[5] M. Yoshitake, et al., "Light emitting device encapsulated with silicones and curable silicone compositions for preparing the silicones", Patent Application US 8,258,502 (2012).

[6] (a) F. de Buyl, M. Janssen, "Innovation in water purification systems with UV-C LEDs and silicone optics", Proceeding of LPS'2017 conference, Luger Research Ed. 2017, pp446-452.
(b) Philips Lighting, "Dow Corning and Philips Lighting Collaborate to Change the Future of UV Purification", Dow Form No. 11-3847-01 (2017).

[7] Gaggione, "Gaggione Achieves Breakthrough New Collimator Design Using Optical-Grade Dow Corning® MS-1002 Moldable Silicone", Dow Form No. 11-3541-01 (2015).

[8] (a) VS Lighting Solutions (Panasonic group), "Pioneering More-Reliable Outdoor LED Lighting Modules with Advanced Optical Silicones", Dow Form No. 11-3578-01 (2015).
(b) Selux Corporation, "Next-Generation Light Engine Shows Improved Performance and Efficiency with Optical Silicones from Dow Corning", Dow Form No. 11-3742-01 (2017).

[9] Schreder, "Dow and Schreder Team up for Eastern Europe's First LED-Illuminated Sports Stadium", Dow Form No. 11-3890-01 (2018).

[10] (a) Hella KGaA Hueck & Co, "Dow Corning brand Moldable Optical Silicones Help Pave the Way to a Groundbreaking LED Headlamp Design from Hella KGaA Hueck & Co", Dow Form No. 11-3675A-01 (2017).
(b) SoundOff Signal, "Emergency Vehicle LED Lighting Gets More Visible and More Rugged with Co-molded Silicones from Dow Corning", Dow Form No. 11-3654-01B (2018).

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Flexible Graphite for Superior Thermal Management Solutions in LED Lighting

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Abstract

LED drivers used in large LED Outdoor Lighting Fixtures require Thermal Interface Materials (TIMs) or Thermal Spreading Materials (TSMs) to maintain components at or below a temperature of 72–85 °C to ensure long life. NeoGraf Solutions and Sur-Seal conducted thermal tests to measure the effectiveness of various solutions in reducing the operating temperatures of LED drivers used in two lighting fixtures, an 800 mA unit rated at 333 W and a 1200 mA unit rated at 511 W.

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Summary – Results

The thermal tests of these luminaires were carried out as follows:

1. Baseline thermal tests of the OEM thermal solutions at 23 °C
2. Thermal tests of SPREADERSHIELD SS300-0.94 FLEX solutions at 23 °C
3. Thermal tests of SPREADERSHIELD SS300-0.94 FLEX solutions at 40 °C
4. Thermal test with no thermal solutions at 23 °C

Test results were as follows:

1. The replacement of the OEM thermal solutions with an SS300-0.94FLX spreader encapsulating the driver reduced the temperature rise on the driver by 4–9 °C (20–37%).
2. The SS300-0.94FLX spreaders provided more uniformity in driver temperatures with the temperature variation within a driver less than 1.4 °C.
3. The SS300-0.94FLX spreaders wrapped around the drivers reduced the thermal resistance of the drivers by 18–37%

With no TIM, the 511-watt unit operating at 40 °C ambient can reach a maximum temperature of ~ 80 °C, which results in an estimated driver lifetime of about 50,000 hours. An SS300 FLX wrap can reduce this maximum to ~ 68 °C and provide an estimated driver lifetime of 100,000 hrs.

Background

LED outdoor luminaires are used on highways, interchanges, ports, rail and container yards, parking areas, etc. LED drivers take the 120–240 VAC input to a luminaire and provide 10–12 VDC needed to power LEDs. Thermal Interface Materials (TIMs) or Thermal Spreading Materials (TSMs) are used to minimize driver temperatures for longer life. NeoGraf Solutions and Sur-Seal conducted tests to measure the thermal performance of SS300 FLX in two luminaires:

1. Outside Flood rated at 511 watts
2. Outside Flood rated at 333 watts

LED drivers used in large LED outdoor lighting fixtures require Thermal Interface Materials (TIMs) or Thermal Spreading Materials (TSMs) to maintain components at or below a temperature of 72–85 °C to ensure long life. Driver temperatures as high as 85 °C can reduce operating lifetimes to as little as 40,000 hours, as shown in Figure 1. Reducing those driver temperatures to 72 °C can increase life to as much as 100,000 hours.

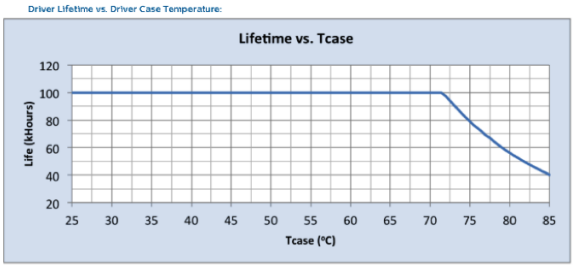

Figure 1: Graph of operating lifetime vs. case temperature for a typical LED driver.

The case temperature of a driver can be reduced and the driver lifetime improved by using an eGRAF SS300-FLX Embossed Flexible Graphite Spreader. This Thick Spreader Material (TSM) is a combined Thermal Interface (TIM) and heat spreader that provides improved performance in LED drivers. The surfaces of SS-FLX are embossed to improve flexibility and conformability and thus improve thermal performance on non-planar surfaces in a fixture or device. SS-FLX products have been used in LED lighting and driver applications and in radiant floors. SS-FLX material is offered in a thermal conductivity of 300 W/m-K in two thicknesses.

1. SS300-0.51-P1GP1A1-FLX (0.51 mm thick)
2. SS300-0.94-P1GP1A1-FLX (0.94 mm thick)

Sur-Seal currently supplies TSMs made from NEOGRAF SOLUTIONS SPREADERSHIELD® SS300-0.94 FLEX in OEM LED luminaires. Sur-Seal and NeoGraf Solutions conducted tests to measure the effectiveness of SS300 FLX in reducing the operating temperatures LED drivers within two LED outdoor luminaires,

1. 333 watt (800 mA unit)
2. 511 watt (1200 mA unit)

These tests were carried out in an environmental chamber as follows:

1. Baseline thermal tests of the OEM thermal solutions at room temperature (23 °C)
2. Thermal tests of SPREADERSHIELD® SS300-0.94 FLEX wrap solutions at room temperature (23 °C)

3. Thermal tests of SPREADERSHIELD® SS300-0.94 FLEX wrap solutions at 40 °C
4. Thermal test with no thermal solutions at 23 °C.

Test Methodology

Two Type T thermocouples were installed on each LED driver. One thermocouple was installed at or near the TC test point on the driver (identified as TC Point) and a second thermocouple was installed as far from the test point as possible (identified as Far Side) as shown in Figure 2. Additional thermocouples were installed inside and outside of the driver housings and on the external mast attachment of the luminaire to its support. Both luminaires were attached to 5-foot-high wooden supports and then placed inside a 12 ft. wide × 15 ft. deep by 10 ft. high environmental chamber and tested simultaneously, Figure 3.

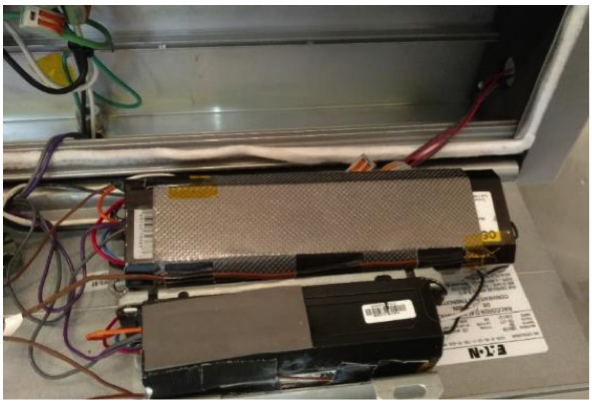

Figure 2: Thermocouples installed on two drivers. Top driver has an eGRAF-SS-FLX TSM wrapped around it. Lower driver has an OEM gap pad solution on one surface.

Test Procedure

The chamber temperature was kept constant during each test using the chamber's heating/cooling control system. Test samples were allowed to equilibrate to test temperature for at least $\frac{1}{2}$ hour prior to the test. Once at equilibrium, power was applied to both luminaires. Thermocouple temperatures were measured every 30 seconds. Tests were continued until thermocouple temperatures stabilized (approximately 2 hours). The temperature rise above ambient was computed for each thermocouple as a function of time. This was done for each temperature, luminaire, power level

Figure 3: Luminaire installed in environmental chamber.

and thermal solution. A typical plot of this data is shown in Figure 4.

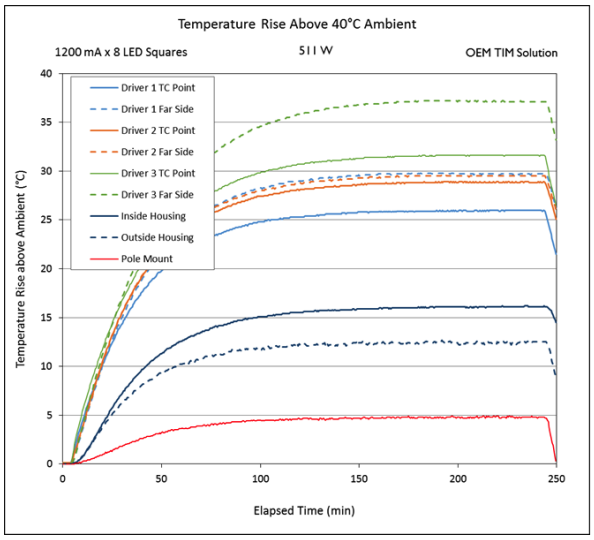

Figure 4: Typical plot of Temperature Rise above Ambient for the 1200 Ma luminaire with an OEM thermal solution in an environmental chamber at 40 °C during a 250 minute thermal test.

The maximum temperature rise above ambient was then determined for each thermocouple as a function of driver and power level, ambient temperature and thermal solution. The Thermal Resistance, RT, of each driver at the TC Point was then calculated from the equation:

$$R_T = \frac{\text{Temperature Rise Above Ambient TCP}}{\text{Individual Driver Power}} \quad (1)$$

The Thermal Resistance is a measure of the efficiency of a thermal solution. It takes into account both the temperature rise above ambient and the amount of power going into the system. The lower the Thermal Resistance, the better the thermal solution.

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Luminaire Construction

One of the luminaires that was tested is shown in Figure 5. The tested luminaires contain 3 LED drivers in a small electrical box that was adjacent to the LED panel modules. The recommended case operating temperatures at TC Point for these drivers is 90 °C maximum, but 85 °C for a 5-year life.

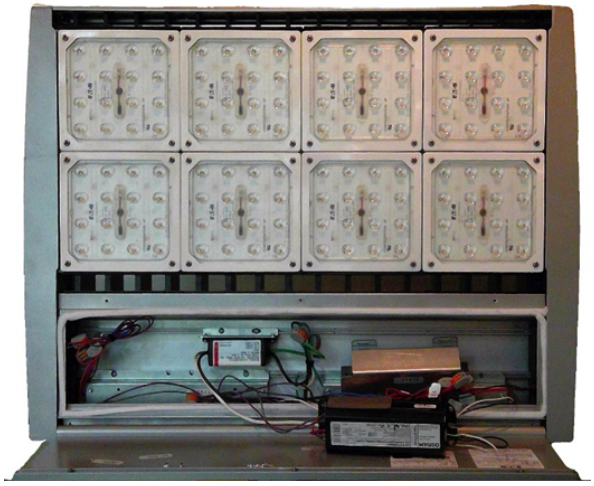

Figure 5: Luminaire with electrical housing open to show 3 LED drivers mounted in a compartment adjacent to 8 LED light squares. One driver is dismounted on the right.

An exploded view of the construction of the 333 watt luminaire, with the OEM solution is shown in Figure 6. In this luminaire there were:

- Two 180 W rated drivers, each operating at 124 watts and powering 3 LED modules
- One 100 W rated driver operating at 85 watts and powering 2 LED panel modules

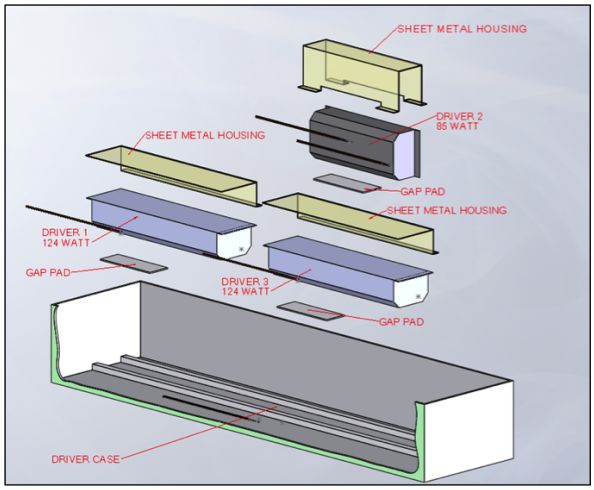

Figure 6: Exploded view of the construction of the 333 watt luminaire with the OEM solution.

As shown, a small elastomeric gap pad TIM is used under Drivers 1 and 3, both of which operate at 124 watts. This gap pad covers about $\frac{1}{2}$ the length of each driver. The drivers are clamped to the driver case using an L shaped bracket with a single mounting flange on one side. Mounting screws attach each housing to the case and press the gap pad against the driver and case.

A similar elastomeric gap pad TIM is used under Driver 2, which operates at 85 watts. This gap pad cover about $\frac{1}{2}$ the length of this driver. The driver is encased in a U shaped sheet metal housing with mounting flanges on both sides. Screws attach this housing to the case and press the gap pad against the driver case

An exploded view of the construction of the 511 watt luminaire, with the OEM solution, is shown in Figure 7. In this luminaire there were:

- Two 180 W rated drivers, each operating at 191 watts and powering 3 LED modules
- One 100 W rated driver operating at 129 watts and powering 2 LED panel modules

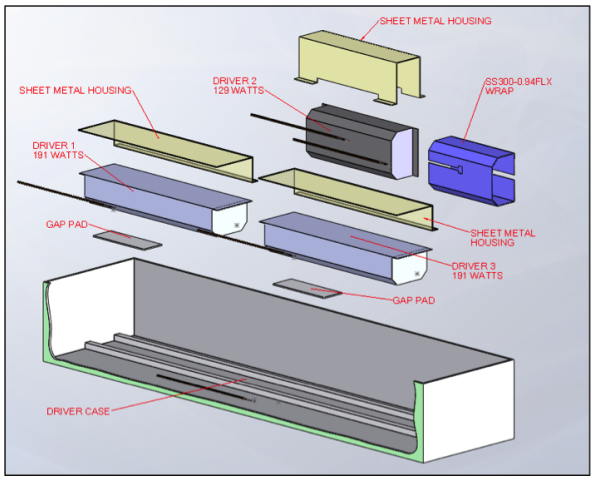

Figure 7: Exploded view of the construction of the 511 watt luminaire with the OEM solution.

As shown, a small elastomeric gap pad TIM is used under Drivers 1 and 3, both of which operate at 191 watts (somewhat above their nominal rating). This gap pad cover about $\frac{1}{2}$ the length of each driver. The drivers are clamped to the driver case using an L shaped bracket with a single mounting flange on one side. Mounting screws attach each housing to the case and press the gap pad against the driver and case. Note that the driver case is too small to use a U shaped housing with mounting flanges on both side for these drivers.

Unlike the previous luminaire, in this OEM design,

Driver 3 is cooled by an SS300-0.94-P1GP1A1-FLX spreader design wrapped around four sides of the driver. This driver operates at 129 watts (somewhat higher than its nominal rating). The spreader and driver are encased in a U shaped sheet metal housing with mounting flanges on both sides. Mounting screws attach this housing to the case and press the narrow faces of the SSFLX spreader against the driver case.

The SS300-FLX wrap solution used on both the 333 watt and 511 watt luminaires is shown in Figure 9. The SS-FLX Wrapped solution is a sheet of SS300-0.94-P1GP1A1FLX wrapped around all four sides of drivers 1, 2 and 3. Note that the OEM SSFLX Wrap on driver 3 was left unchanged in the 511 watt unit.

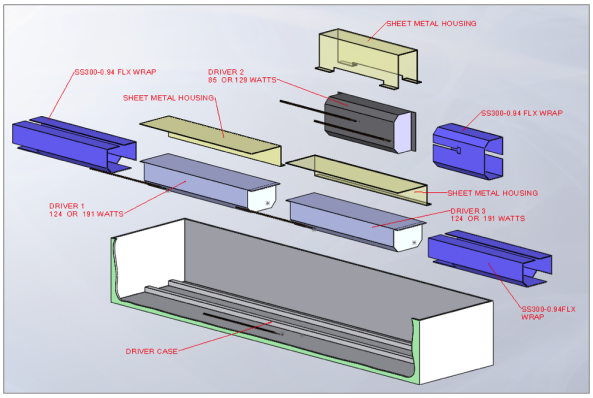

Figure 8: Exploded view of the construction of the 333 watt and 511 watt luminaire with the SS300-FLX wrap solution on all three drivers.

Temperature Rise above Ambient of the Drivers

The temperature rise above ambient at the TC point as a function of driver, thermal solution and ambient temperature is shown in the bar chart for the 333 watt Luminaire, Figure 9 and the 511 watt luminaire, Figure 10. In every case where the SS-FLX wrap replaced the OEM solution, there was a significant drop in the temperature rise. This drop ranged from 3.7–9.2 °C or 20–37%. Note that in the 511 watt luminaire there is no change in the temperature rise on Driver 2 since the OEM solution is the SS-FLX wrap solution.

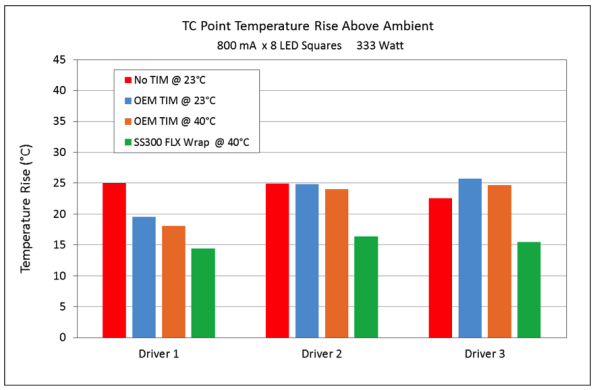

Figure 9: Temperature rise above ambient for the 333 watt luminaire.

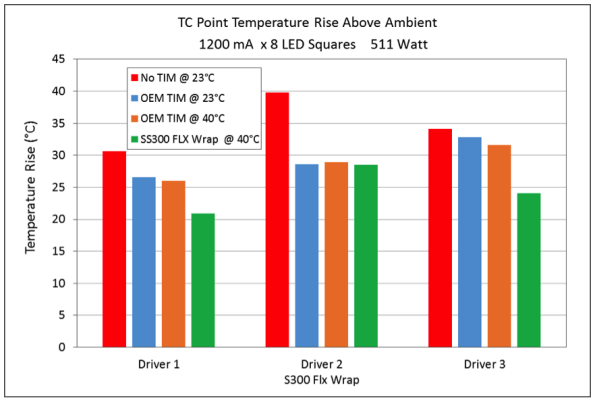

Figure 10: Temperature rise above ambient for the 511 watt luminaire.

Thermal Resistance of the Drivers

The thermal resistance of each driver at the TC Point is shown in the table below as a function of luminaire, wattage, thermal solution, and ambient temperature. The average and maximum thermal resistance of the drivers is also shown. Note that the thermal resistance of the OEM designs are approximately equal at 23 °C and 40 °C. This is because thermal resistance is essentially independent of ambient. The maximum thermal resistance for each luminaire is shown in red.

The thermal resistance is generally highest in the 511 watts unit. Driver 3 has the highest thermal resistance in the 511-watt unit, while Driver 2 has is the in the 333-watt unit. The SS300 FLX wrap solution always has the lowest thermal resistance, and is 18–33% lower than the OEM solution.

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Luminaire	Thermal Solution	Ambient	Thermal Resistance at TC Point				
			Driver 1 (°C/W)	Driver 2 (°C/W)	Driver 3 (°C/W)	Average (°C/W)	Maximum (°C/W)
1200 mA x 8 LED Squares 511 Watts	No TIM	23°C	0.32	0.31	0.36	0.33	0.36
	OEM TIM	23°C	0.28	0.22	0.34	0.28	0.34
	OEM TIM	40°C	0.27	0.22	0.33	0.28	0.33
	SS300 FLX Wrap	40°C	0.22	0.22	0.25	0.23	0.25
800 mA x 8 LED Squares 333 Watts	No TIM	23°C	0.20	0.29	0.18	0.23	0.29
	OEM TIM	23°C	0.16	0.29	0.21	0.22	0.29
	OEM TIM	40°C	0.15	0.28	0.20	0.21	0.28
	SS300 FLX Wrap	40°C	0.12	0.19	0.13	0.14	0.19

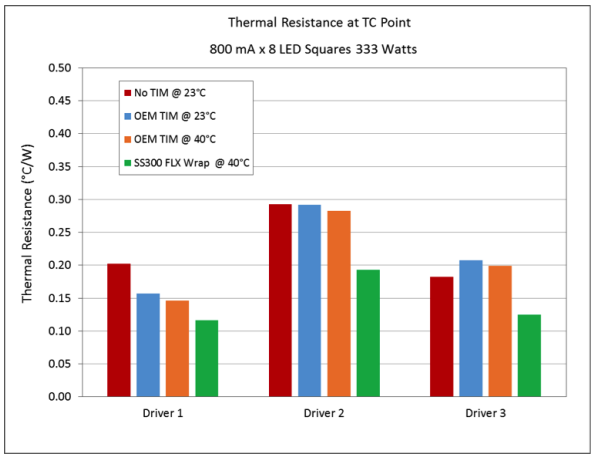

Figure 11: Thermal resistance for the 333 watt luminaire.

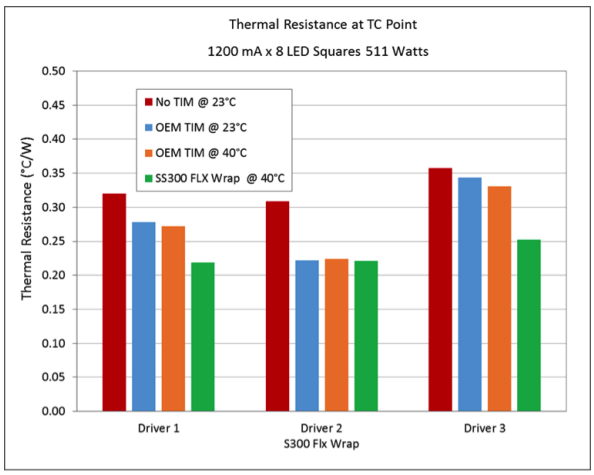

Figure 12: Thermal resistance for the 511 watt luminaire.

Temperature Uniformity within the Drivers

The temperature uniformity within the drivers on the 511 watt unit is shown in the table below. The table shows the maximum temperature rise, above the 40 °C ambient, at the TC Point and the Far Side of the drivers. The data for the OEM TIM is also shown in Figure 13 and that of the SS300-FLX Wrap is shown in Figure 14.

For Drivers 1 and 3, this difference ranged from 3.8 to 5.6 °C for the OEM TIM. Replacing the OEM solution with an SS300 FLX wrap reduced this to 0.5 to 0.8 °C. Driver 2 was wrapped with SS300

Luminaire	Ambient (°C)	ΔTemperature Abs(TC point - Far Side)		
		Driver 1 (°C)	Driver 2 (°C)	Driver 3 (°C)
511 Watt OEM TIM	40	3.8	0.7	5.6
511 Watt SS300FLX Wrap	40	0.8	0.1	0.5

FLX as part of the OEM solution. Applying the SS300 FLX to the other drivers also affected this driver, lowering its difference from 0.7 to 0.1 °C.

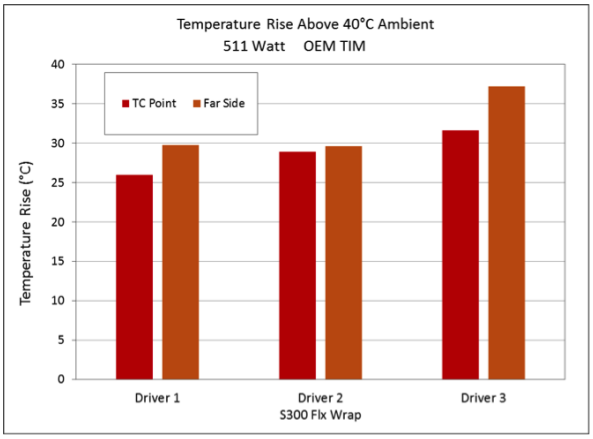

Figure 13: Maximum temperature rise above the 40 °C ambient at the TC Point and the Far Side of the drivers in the 511 watt unit with the OEM TIM.

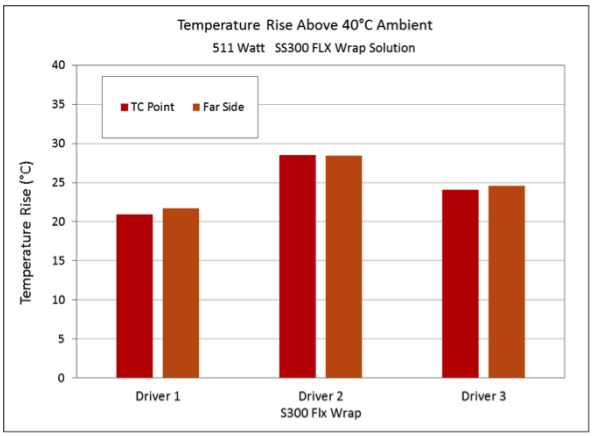

Figure 14: Maximum temperature rise above the 40 °C ambient at the TC Point and the Far Side of the drivers in the 511 watt unit with the SS300-FLX Wrap.

The temperature uniformity within the drivers on the 333 watt unit is shown in the table below. The table shows the maximum temperature rise, above the 40 °C ambient, at the TC Point and the Far Side of the drivers. The data for the OEM TIM is also shown in Figure 15 and that of the SS300-FLX Wrap is shown in Figure 16.

Luminaire	Ambient (°C)	ΔTemperature Abs(TC point - Far Side)		
		Driver 1 (°C)	Driver 2 (°C)	Driver 3 (°C)
333 Watt OEM TIM	40	0.0	1.5	1.5
333 Watt SS300 FLX Wrap	40	1.2	0.0	1.4

The variation in the drivers was 1.5 °C for the OEM TIM. Replacing the OEM solution with an SS300 FLX wrap reduced this variation to 1.2 to 1.4 °C.

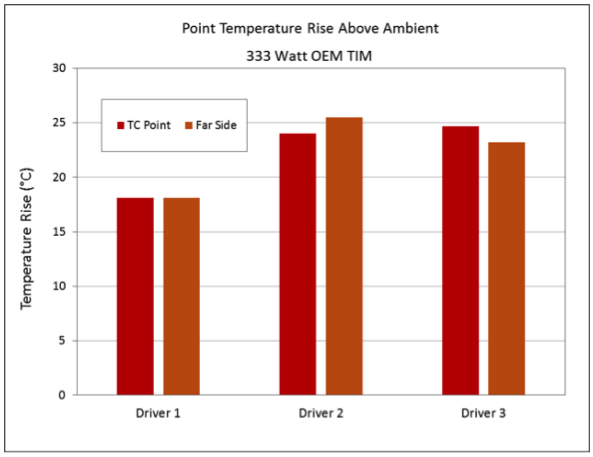

Figure 15: Maximum temperature rise above the 40 °C ambient at the TC Point and the Far Side of the drivers in the 333 watt unit with the OEM TIM.

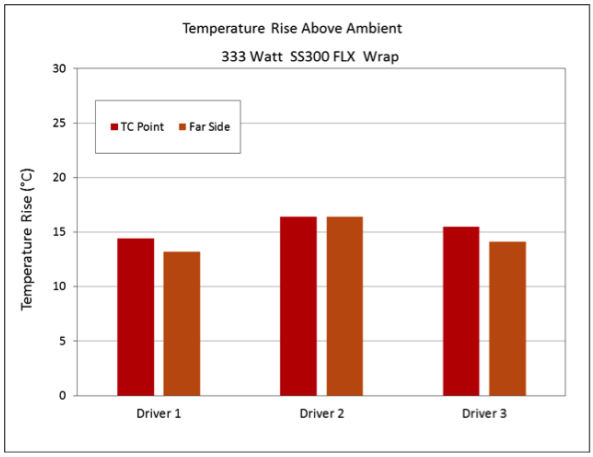

Figure 16: Maximum temperature rise above the 40 °C ambient at the TC Point and the Far Side of the drivers in the 333 watt unit with the SS300-FLX Wrap.

Conclusions

SS300-FLX solution outperformed the OEM Solution on every driver.

Maximum Driver Temperature

The SS300 FLX Wrap reduced maximum driver temperatures from 72–77 °C to ~ 68.5 °C

Temperature Rise above Ambient

The SS300-0.94FLX Wrap reduced the temperature rise on driver TC Points by 4–9 °C (20–37%) and reduced the Far Side driver temperature rise by 5–9 °C (27–39%)

Thermal Resistance

The SS300 FLX Wrap reduced the driver thermal resistance by 18–37%

Temperature Uniformity

SS300-0.94FLX Wrap reduced to temperature variation within a driver to less than 1.4 °C

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Aluminum Oxide PCB - Technology for Developing New Generation LED Solutions

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Abstract

The LED industry is developing and posing new challenges to manufacturers of LEDs, PCBs, thermal interfaces and cooling systems. In particular, PCB manufacturers for LED applications solve conflicting tasks:

1. dielectric thermal resistance reduction - increase of the breakdown voltages;
2. placement of LEDs, current supply and control circuit in a single module with limited area - ensuring a uniform luminous flux and using standard lenses.

In fact, these points send developers to the laminate material (substrate) that combines the advantages of ceramics in terms of thermal management and high electrical strength, and FR4, which provides the flexibility of transition between layers at low price. Al oxide production experienced team has achieved the following results in serial production:

1. high thermal conductivity of the dielectric of 12–24 W/(mK);
2. breakdown voltage up to 7000 V DC;
3. double-sided PCBs with metallized vias.

These results enable to design high-power LED modules with high-densed chains of LEDs and with current supply elements placed on the PCB reverse side. Such solutions can be considered as analogues of Chip-On-Board AC (COB AC) technology. These solutions are a response to customer requests, not only in terms of technical requirements, but also pricing policy, and are keeping pace with the LED market trends.

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Introduction

In the development of modern microelectronics, in accordance with the generalized Moore's law, processes of miniaturization and simultaneously increase in a level of power used, current and voltage densities are going in parallel. The problem of heat removal arising in this connection is solved by a huge number of different methods in different applications, and the possibility of choosing a particular tactic of solving the problem of heat removal is limited only by the imagination of designers, engineers and economic considerations.

In addition, due to the necessary resistance to various kinds of impacts during operation and also associated with this desire to simplify the design of products, passive elements for heat removal remain extremely popular. The central role in this case is played by the possibility of heat removal, while at the same time resistance to high voltages and the possibility of high density installation, allowed directly by the laminate material from which the PCB is made.

LED lighting is one of the industries that shows the greatest interest in terms of the needs of the world market to resolve the identified problems. At the same time, the key factor is the need to reduce the cost of devices, including PCBs and materials for their manufacturing.

In the field of LED lighting has de-facto gone though not only technical but also consumer revolution and at the moment there is a targeted reduction in the cost of final products through the use of various technical techniques and various practices, including borrowed from other segments of electronics, microelectronics, photovoltaics, etc.

One of solutions of objectives is Aluminum Oxide (al oxide) PCB. Al oxide PCB is an innovative product of high technology developer and manufacturer RUSALOX. Manufacturing process is based on unique aluminum oxide (al oxide) technology, which provides high cooling efficiency of any heat-dissipating electronic components. Solutions based on high thermal conductive al oxide PCBs meet current market and customer requirements and R&D projects respond to modern challenges of the lighting industry.

Aluminum Oxide Technology

The main difference between Insulated Metal Base PCBs (IMS) and al oxide PCBs is the nature of the dielectric[1]. The substrates produced by aluminum oxide technology consist of three main parts: conductive layers, aluminum and dielectric layer with nanoporous structure. This dielectric allows to provide high thermal conductivity of the oxide-aluminum system up to 120 W/(mK) and determines the competitive advantages of the existing aluminum oxide technology of PCB RUSALOX in comparison with products in which prepreg is used as a dielectric.

The main stages of the process are shown in Figures 1 (for clarity, single LED PCB is demonstrated).

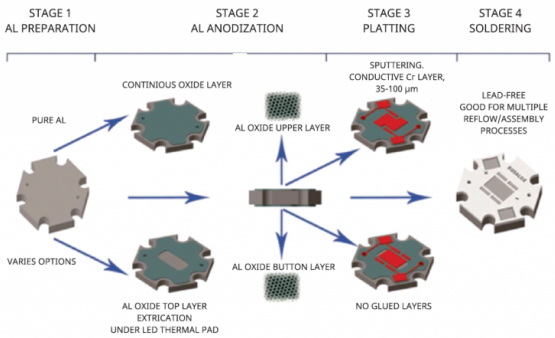

Figure 1: Overview of production stages of aluminum oxide PCB.

The core of the al oxide PCB manufacturing is electrochemical processes of deep aluminum oxidation and deposition followed by the copper layer plating. These processes represent the main difference from the standard-to-industry IMS manufacturing operations and determine the benefits of al oxide PCB both in the field of thermal management and in solving design problems. The unique feature of al oxide technology is that the manufacturing process uses the well-known technological operations to create a completely new product.

Controlled oxidation allows to control the thickness of the alumina layer and its pattern. As a result, it is possible to perform extrication under LED (and any other heat-dissipating component) thermal pad. This provides almost direct contact of the thermal pad with the aluminum base, as shown in Figure 1.

Due to their thermal characteristics, al oxide PCBs enable high-density mounting of high-power and extra high-power LEDs on a limited area. For

instance, the al oxide LED module called “ALENA 180Y19” with 180 LEDs Seoul Semiconductors SZ8-Y19-W0-C7-W3, 567 W, ⌀55 mm (high power density), shown below on Figure 2.

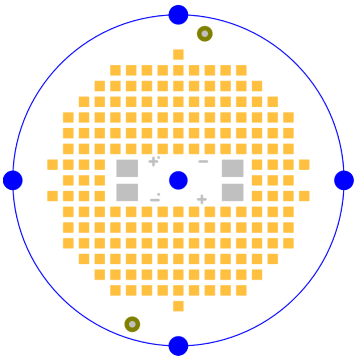

Figure 2: Module ALENA 180Y19.

This module is a full functional cost effective substitute to ceramics COB.[1]

Dielectric Strength

As per now, a typical value of dielectric strength of al oxide PCB is 2500–4000 V DC, depending on the PCB design and its complexity. RUSALOX is systematically conducting R&D projects and seeking for new engineering solutions and applications for al oxide material. Currently, the key R&D direction is underway to increase the breakdown voltage to 6000–7000 V. High breakdown voltages of 5000–7000 V enable al oxide PCBs to be used in the most demanding applications where dielectric strength and thermal management are critical.

To ensure high breakdown voltage of any IMS, in addition to taking into account the electrical strength of the dielectric layer, it is necessary to properly design PCBs, namely to ensure the distance between the copper tracks and the open metal parts: edges of PCB along the contour, in the grooves and in the holes; cap screws. The aluminum oxide technology allows performing double-sided boards with an average neutral heat-conducting layer, which allows, for example, an aluminum base to be used as a “ground” circuit, or as a heat sink with direct thermal contact with electrically neutral thermal led thermal pads. Such circuits shall also be located at a distance providing the required breakdown voltages, Figure 3.

In Figure 3, value “b” is the distance from which breakdown voltage of a PCB depends. The minimum suggested distance of value “b” is 3 mm,

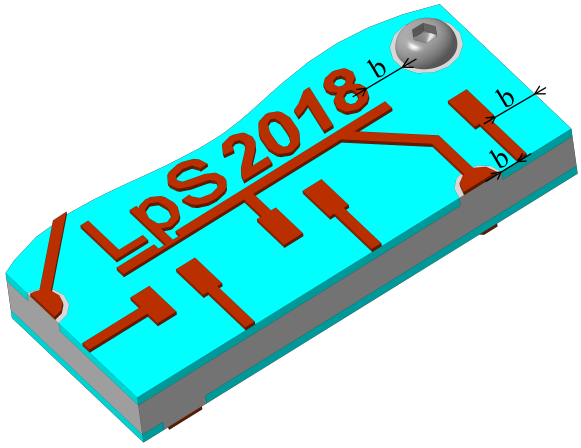

Figure 3: Three-layer al oxide PCB.

even though the recommended distance is generally something ranging from 5–7 mm when feasible. [4] Approximately we assume that the 1 mm of value “b” guarantees ∼ 1000 V.

The corresponding electrical strength of the dielectric layer (oxide) allows producing analogues COB AC or DOB (Driver on Board) LED module, illustrated in Figure 4.

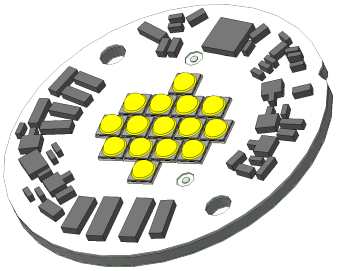

Figure 4: Module “E1449”.

Module “E1449” is a standard layout of DOB LED module: LEDs and current supply elements placed on top layer of the PCB.

Metallized Vias

Thanks to years of experience and mastering of via metallization in aluminum oxide technology, double-sided PCBs with PTH with diameter from 0.4 mm are now also not a myth. Current supply elements placed on the PCB reverse side, Figure 5.

For clarity, in Figure 5, the bottom side of the al oxide PCB is laid out in layers: components, solder mask, copper, oxide. Vias do not only open up new possibilities for the layout of components on the PCBs, but also create an aesthetic

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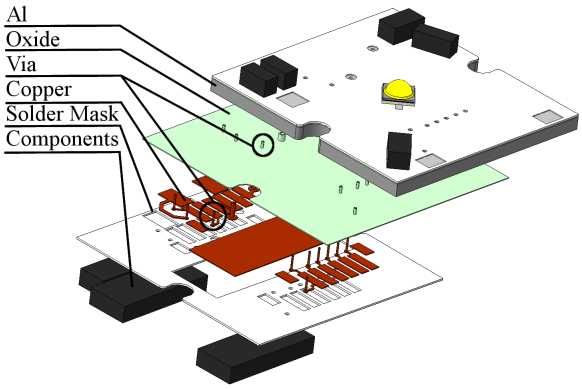

Figure 5: DOB with vias.

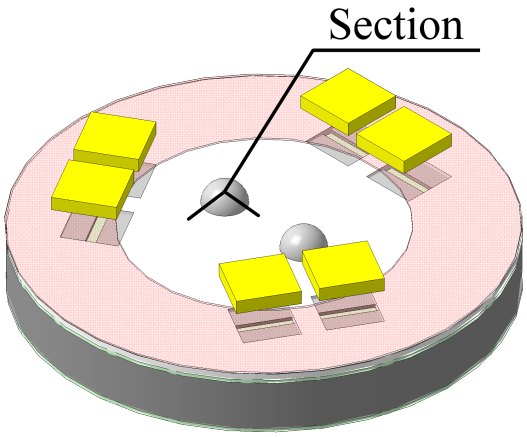

Figure 7: Module LED Z8Y19.

appearance if necessary. The striking example is the project of the car reverse lamp “LOCATOR W16W”, Figure 6, which uses the module “6LED Z8Y19”.[5]

Figure 6: LOCATOR W16W.

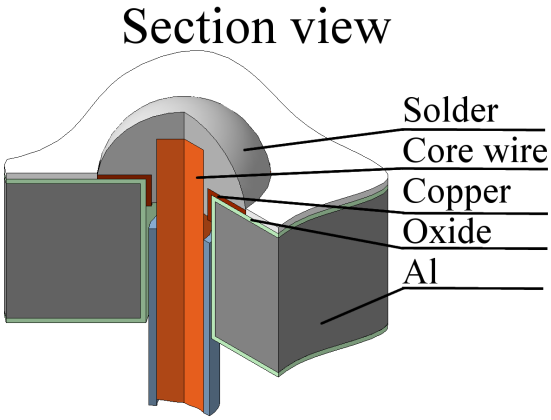

Figure 8: Section view.

The module diameter is 13.9 mm, where 6 LEDs Z8 Y19 Seoul Semiconductor are placed, module power is 16 W, flux is 1750 lm, supply voltage is 12–15 V. While designing this module, it was decided not to use connectors for connecting wires, mainly for two reasons:

1. due to the limited cost of the product, which is very critical and, thus, typical for the automotive industry;
2. restricted area due to the nature of the product.

It was decided to mount wires through the holes, and as mounting points the customer wanted to see two neat drops of solder, clearly shown in Figure 7 and 8.

The wiring option shown in Figure 8 is virtually impossible on standard IMS due to the high probability of defects in breakdown voltages. In al oxide PCB this problem is solved by oxidation of holes. The area of contact of the heatsink to the bottom side of the PCB is limited (shown conditionally in red in Figure 7), while the thermal power is high enough. Due to the high thermal conductivity of al oxide PCB, the temperature of the LED crystal does not exceed the permitted value.

This is just an example of what kind of tasks can be solved by al oxide material, but the technological opportunities and features for manufacturing modules based on aluminum oxide go far beyond the said earlier:

1. mounting SMD components on an insulated conductor;
2. mounting SMD components on a common layer (aluminum base);
3. assembling PTH components into isolated hole;
4. assembling PTH components on a common layer (aluminum base);
5. creation of vias in layers through insulated holes.

Comparison With Ceramics

The key technical requirements that force manufacturers to use ceramic substrates can be divided into two parts:

1. the need for high thermal conductivity for heat dissipation;
2. high breakdown voltage level.

Since the main driver of any economic decision is cost of a final product, in cases where one of the two requirements can be mitigated, it is possible to use alternative materials, which the laminate market is eagerly developing and seeking for.

Parameters of al oxide material allow using it not only as a standard circuit, but also as ceramic substrate materials for mid and high LED (UV, IF or COB modules) or power modules in a range industries and special applications. In addition to the LED industry, the problem of heat removal is very important in modern power electronics devices, such as IGBT, IPM, DIPIPM modules and microwave bridges. The majority of such power modules manufacturers often use the sintered alumina ceramics (Al_2O_3) and expensive alumina nitride ceramics (AlN) as substrates for their high voltage and high power devices. The standard structure of IGBT module involves the use of a baseplate, made of copper or aluminum, which is attached to the ceramic substrate through TIM. This design significantly increases the cost of a power module, and the presence of clued (joined) between themselves components affects reliability and service life of a device.

Substrate for power modules, in particular IGBT modules, manufactured following RUSALOX al oxide technology, allows not only to use a cost-effective product with high thermal conductivity, but not to eliminate a baseplate as the al oxide material itself is a composite material with a metal base, which successfully replaces both substrate and baseplate within modern power modules.

Worth noting, this approach does not only comply with power electronics trends but also with optoelectronics, thermoelectronics, where combination of baseplate and ceramic substrate is frequently used.

Comparison between al oxide material, Al_2O_3 ceramics and AlN ceramics as base materials is presented in Table 1. The approximate model was used in the calculations of thermal resistances (R) [2]

$$R = \frac{h}{k * S}, \quad (1)$$

where value "h" is material thickness, value "k" is thermal conductivity, value "S" is an area, thermal resistance of al oxide material is a sum of thermal resistance of aluminum and thermal resistance of modified alumina (oxide layer).

Table 1: Comparative characteristics of al oxide material, Al_2O_3 ceramics and AlN ceramics.

Parameter of substrate	Al_2O_3 ceramic	AlN ceramic	Al oxide
Area, mm	100	100	100
Thickness	1.5 mm	1.5 mm	Oxide thickness: 60 µm, Al thickness: 1.5 mm
Thermal conductivity, W/(Km)	24	150 mm	Oxide thickness: 12 W/(Km), Al thickness: 200 W/(Km
Thermal resistance, K/W	0.625 mm	0.1 mm	0.125

Table 1 shows that the thermal resistance of al oxide is less than that of Al_2O_3 ceramic, and is close to the thermal resistance of AlN ceramics. Integral thermal conductivity of al oxide substrate is approximately 120 W/(Km) for this example. But al oxide technology allows managing the thickness and pattern of the oxide layer [3] and due to this, the thermal conductivity can be more than 150 W/(Km).

Conclusions

Rusalox innovative solutions enable better thermal, higher functionality and lighter weight for wide range of applications including high power LED lighting, UV and IF lighting and curing systems, COB AC and DOB, power boards for

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various applications including IGBT, MOSFET modules, and power RF boards.

Through years of researches and experiments, RUSALOX has managed to achieve outstanding quality of its high thermal conductive al oxide boards meeting all specific demand of partners. All al oxide products meet the strictest standards of ISO9001:2008, are compliant with RoHS and UL recognized.

Rusalox aluminium oxide technology still remains a broad process platform and is used in different electronics products, such as Chip-On-Board (COB), automotive lighting, UV lighting, microwave electronics, SiP systems (System in Package), SOC systems (System on Chip), high-capacity modules, IGBT modules, Peltier elements, etc.

References

[1] O. Morozova “Equivalently equal electrical, optical and thermal parameters open new design possibilities of LED devices” // LED Lighting Technologies — Smart Technologies for Lighting Innovations. — 2017.

[2] MCPCBs for LED Applications. Thermal Management Material Specifications // heatsinks.files.wordpress.com URL: https://heatsinks.files.wordpress.com/2011/02/mcpcbs-for-led-applications.pdf (11.06.2018).

[3] Naish M., Besprozvanny E., Muzalevskiy I., Osin A., Belov D., Skvortsov K. “RUSALOX” — the thermal management solution // Modern lighting technology. - 2014. - N.5. - p. 66–70.

[4] Mauro Ceresa. Cree — Electrical over stress — how to prevent an LED failing earlier than expected //LED professional.-2018.-N.66. - p. 70–78.

[5] LOCATOR W16W // Light-label URL: http://light-label.ru/produktsiya/LOCATOR-W16W/ (20.06.2018).

Cost-Effective Manufacturing of High-Quality ITO Thin Films on 300 mm CMOS for Next Generation Display Technologies

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Abstract

High-quality indium tin oxide (ITO) layers were deposited on 12" Si and Si/500-nm-thermal-SiO_2 wafers in an industrial multi-chamber CLUSTERLINE® 300E magnetron sputtering system. To obtain the desired physical properties, the ITO-coated wafers were post-annealed in-situ as part of the best known method (BKM) fabrication flow. Glancing angle X-ray diffraction (GAXRD) measurements revealed that the ITO films exhibit a cubic crystal structure with a strong (222) preferred orientation and an average grain size of 8.5 nm. Thickness uniformity of the 25-nm-thick ITO layers that underwent a post-annealing at 340 °C was below 2.8% as obtained from ellipsometry measurements, and the absolute and peak-to-value roughnesses measured by means of atomic force microscopy (AFM) were 0.1 and 2.3 nm, respectively. Moreover, the average sheet resistance of these layers measured by means of the four-point probe technique was 68.2 Ω/sq (electrical resistivity 171.7 μΩ cm) with an uniformity of 3.4%, and the corresponding optical transmission at 450 nm was 97.7%. High volume manufacturing was demonstrated, achieving outputs of more than 45 wafers/hour using multiple ITO process chambers and post-annealing units.

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Introduction

Owing to its exceptional optical and electrical properties, indium-tin oxide (ITO) is nowadays the material of choice for providing transparent electronic conduction in nearly all flat panel displays used in TV screens, laptop computers and mobile phones, regardless of whether they are based on liquid-crystal display (LCD) or organic light-emitting diode (OLED) technologies [1][2][3]. However, emerging applications of wearable electronics and augmented reality have very demanding technical requirements in terms of brightness, response time, contrast ratio, energy efficiency and advanced packaging density which can no longer be met by these display technologies [4].

The new microLED technology is currently considered as one of the most promising solutions that would offer the levels of performance required by next generation display market applications [5][6][7][8][9][10][11]. As the name implies, microLED displays consist of arrays of microscopic LEDs forming the individual pixels. Whether these displays need to be fabricated by hybridization of microLED arrays with the CMOS active matrix using the flip-chip technology, or by monolithic hybrid integration, successful realization of microLED-based devices requires front end semiconductor manufacturing approaches and handling standards for the thin film processes involved [12].

For the transparent conductive ITO layers this means an absolute control of particles and defects, single wafer traceability, and compatibility with standard 12" manufacturing technology [12]. Improved heating uniformity is needed, especially for achieving uniformly high optical transmission and low ITO resistivity. Last but not least, the control of surface morphology and ITO layer roughness is essential for the fabrication of microLEDs, because these characteristics are usually transferred to the functional layers grown on ITO that act as injection, transportation and emission layers, and can therefore be detrimental to the device performance [13].

In this work, we investigate the physical properties of high-quality ITO layers fabricated by a physical vapor deposition (PVD) process on 12" Si and Si/500 nm-thermal-SiO_2 wafers in an industrial multi-chamber CLUSTERLINE® 300E magnetron sputtering system [14].

Experimental

Clusterline 300E

Figure 1 presents the layout of the deposition system, which consists of a rapid atmospheric front-end module (AFEM) in a Class 1 mini environment and a vacuum section. The AFEM components are: i) FOUP load port modules (FLPM) with up to four 300 mm load-port cassette stations; ii) four-axis atmospheric robot with mapping functions to detect cross-slotted, double loaded wafers and instant wafer slide out detection at cassette stations; iii) wafer aligner for rotational pre-alignment and centering of wafers. If required, the AFEM can be equipped with an atmospheric batch degas module, a wafer flipper and a buffer station for up to 12 wafers.

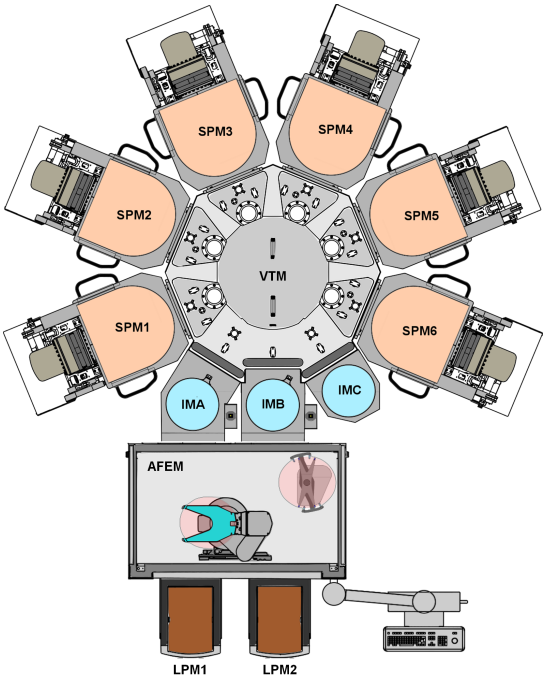

Figure 1: Layout of CLUSTERLINE®300E magnetron sputtering system for depositing ITO layers. AFEM is a rapid atmospheric front-end module, SPM1 to SPM6 are six single wafer process modules, VTM is central vacuum transfer module, and IMA, IMB and IMC are three index modules.

The vacuum section can be configured with up to six single wafer process modules (SPM) that can be either PVD or inductively coupled plasma (ICP) soft etch modules, and up to three interface modules (IM) clustered around a central vacuum transfer module (VTM) equipped with a bi-symmetric-arm robot. A PVD module can be configured with direct current (DC) or pulsed DC sputter sources, with uniformity compensation over target life. Moreover, for deposition of compound materials, the module can be equipped

with multiple sources (i.e., up to 4 radio-frequency (RF) or DC), and a rotating chuck for optimum thickness uniformity. For high aspect ratio applications, highly ionized PVD sources based on high power impulse magnetron sputtering (HIPIMS) technology are also available. The chuck tops are available in metal or ceramic versions, either with mechanical clamping, electrostatic chuck (ESC) with shadow mask and gas conduction back side heater/cooler for precise temperature control or clampless chuck with shadow mask. Controlled chuck temperature is available from –30 °C to 500 °C, and an optional RF bias can be applied to the chuck. If required (i.e., in case the deposited layers have to be structured for device applications), the tool can be configured with medium frequency RF plasma based ICP soft etch process modules that can enable high etch rates (ITO removal $> 0.8\,\mathrm{nm/s}$) and excellent uniformity at low bias voltages. The IM stations can consist of air-locks, active vacuum buffers, high-pressure or lamp degas and cooler components.

Deposition of ITO Layers

ITO layers were deposited by DC magnetron sputtering on 12" Si and Si/500 nm-thermal-SiO_2 wafers in the SPM4 module from an In_2O_3/SnO_3 (90/10 wt%) long-life (~1500 kW h) round target in an Ar^+ O_2 atmosphere at a pressure of 2.8×10^{-3} mbar (base pressure 4×10^{-8} mbar). To obtain the desired electrical conductivity and optical transmission, the ITO-coated wafers were annealed without breaking the vacuum in a high-pressure (e.g., 20 mbar) degasser module at temperatures ranging from 200 to 340 °C as part of the best known method (BKM) fabrication flow.

Metrology

Layer thickness and refractive index were measured with a fast spectroscopic Woollam M-2000 Nano ellipsometer using both a 49 point circular pattern with a 10 mm edge exclusion and a 31 point linear scan through the center of the wafer with 5 mm edge exclusion (i.e., from –145 mm to 145 mm). Surface morphology, absolute roughness (R_a) and peak-to-valley (i.e., maximum) roughness (R_{pv}) were determined by means of atomic force microscopy (AFM) using a Park Systems NX20 microscope, where R_a and R_{pv} are defined as:

$$R_a = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N}\left|z\left(x_m, y_n\right) - \langle z\rangle\right| \quad (1)$$

$$R_{pv} = \max_i |z_i| - \min_i |z_i| \quad (2)$$

where

$$\langle z\rangle = \frac{1}{MN}\sum_{m=1}^{M}\sum_{n=1}^{N} z\left(x_m, y_n\right) \quad (3)$$

The degree of crystallinity and microstructure of ITO layers (e.g., fiber texture, average grain size) were probed by glancing angle X-ray diffraction (GAXRD) measurements (incidence angle of 1°) using a Bruker D8 Discover diffractometer equipped with a Cu X-ray tube and a parabolic graded multilayer mirror on the primary arm, and a Soller slits in front of the scintillation detector on the secondary arm. The preferred orientation (fiber texture) was characterized by the corrected Harris texture index for (*hkl*) planes [15]:

$$T_{hkl} = \frac{I_i^{(hkl)}/I_0^{(hkl)}}{\frac{1}{N}\sum_{i=1}^{N} I_i^{(hkl)}/I_0^{(hkl)}} \quad (4)$$

where $I_i^{(hkl)}$ and $I_0^{(hkl)}$ are the intensities of the (*hkl*) Bragg peaks in the GAXRD patterns of the sputtered ITO layers and an In_2O_3 random powder, respectively. The average grain size (D) was determined by using the Williamson-Hall method [16]:

$$\beta_{hkl}\cos\theta = \frac{k\lambda}{D} + 4\varepsilon\sin\theta \quad (5)$$

where β_{hkl} is the full-width at the half maximum (FWHM) of the (*hkl*) Bragg peaks in radians corrected by the resolution function, θ is half of the Bragg angle, $\lambda = 0.154$ nm is the wavelength of the K_α line of the X-rays generated by the diffractometer Cu tube, $k = 0.9$ is the shape factor, and ε is the micro-strain (i.e., strain induced in grains due to crystal imperfections and distortion).

The film transmission measurements were performed on a Perkin Elmer (Lambda 750) UV/VIS Spectrometer. The sheet resistance (R_s) of the ITO layers was determined using a KLATencor OmniMap RS100 four-point probe mapping system on both a 49 point circular pattern with a 10 mm edge exclusion and a 30 point diametric scan with 5 mm edge exclusion (i.e., from –145 mm to 145 mm). Film thickness and R_s uniformities, e.g., U and R_s U, were calculated with the following formula:

$$U\,[\%] \quad \text{and} \quad R_s\,U\,[\%] = \frac{\mathrm{Max} - \mathrm{Min}}{\mathrm{Max} + \mathrm{Min}} \cdot 100 \quad (6)$$

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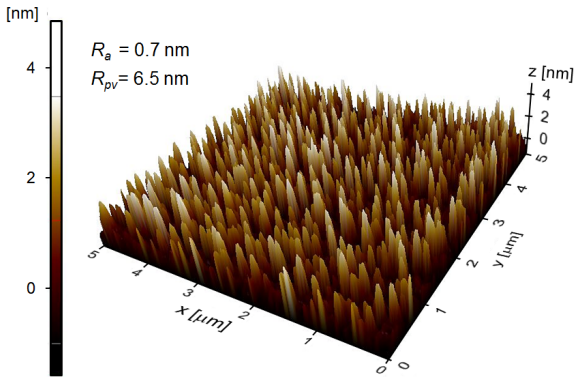

Figure 2: AFM image of a 25-nm-thick ITO layer deposited on a 12" Si wafer before the optimization of process parameters, where R_a and R_{pv}. are the corresponding absolute and peak-to-value roughnesses.

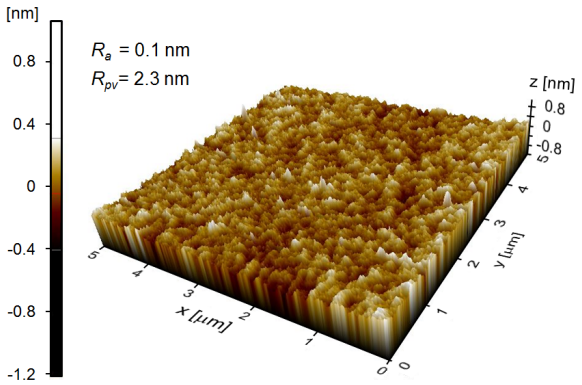

Figure 3: AFM image of a 25-nm-thick ITO layer deposited on a 12" Si wafer after the process optimization, i.e., using the BKM fabrication flow.

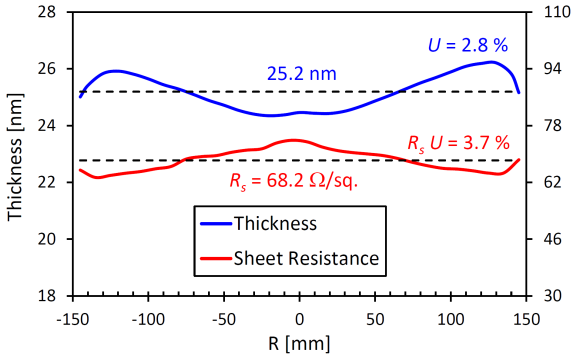

Figure 4: Thickness and sheet resistance profiles of a 25-nm-thick ITO layer deposited by BKM fabrication flow on a 12" Si/SiO_2. wafer, and the corresponding uniformities.

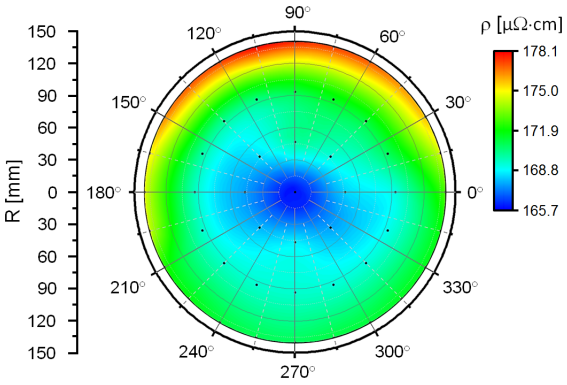

Figure 5: Resistivity distribution of a 25-nm-thick ITO layer deposited on a 12" Si/SiO_2. wafer by the BKM fabrication flow, obtained by multiplying the measured thickness and sheet resistance distributions.

Results

Process optimization

Process parameters (e.g., sputter power, pressure, O_2 content, post-annealing temperature and time, ITO target-to-substrate distance) were optimized such that the resulting surface roughness and sheet resistance were minimized. Figures 2 and 3 show two AFM images of a 25-nm-ITO thick layer sputtered on a 12" Si wafer before and after the process optimization, respectively. Both layers underwent a post-annealing treatment in the high-pressure degasser at 340 °C.

Thus, the ITO surface exhibited many spikes before the process optimization, and that was reflected in large roughness values (e.g., R_a = 0.63 nm and R_{pv} = 6.44 nm). Interestingly, the sheet resistance was also high (e.g., $R_s > 100\,\Omega/\text{sq}$ and $\rho > 250\,\mu\Omega\,\text{cm}$). However, after the process optimization the spikes at the surface were no longer present, and the ITO layer roughness and sheet resistance were dramatically reduced, e.g., R_a = 0.1 nm, R_{pv} = 2.3 nm, and $R_s = 68.2\,\Omega/\text{sq}$ (ρ = 171.7 µΩ cm). The difference between surface morphologies of the ITO layers before and after process optimization is even more striking if one takes into account that the height scale in Figure 2 was reduced by a factor $\sim$ 2.5! The power density on the ITO target, O_2 concentration, post-annealing temperature and post-annealing time for the optimized process (i.e., BKM flow) were 0.8 W/cm^2, 0.74%, 300 °C and 60 s, respectively.

Thickness and sheet resistance of the ITO films on the 300 mm wafers during the 1500 kW h target life were tuned by appropriate choice of the magnet array system behind the ITO target and process parameters in the high-pressure degasser. Thus, the thickness and sheet resistance of a 25-nm-thick ITO layer deposited by the BKM fabrication flow on 12" Si and Si/SiO_2 wafers exhibited quasi-radial distributions with

corresponding uniformities for the whole (i.e., 10 mm edge exclusion) wafer of 2.8 and 3.7%, respectively (see Figure 4).

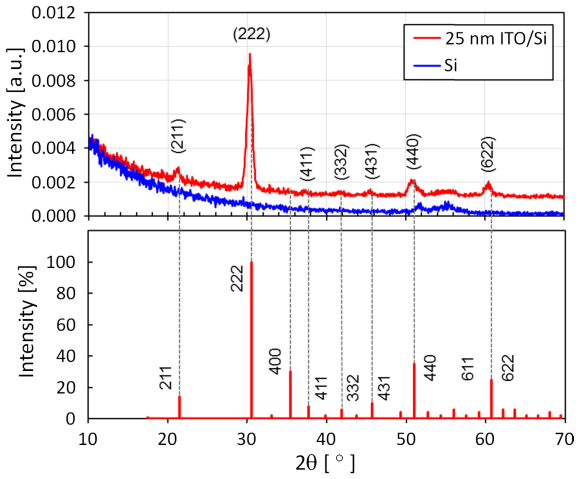

Figure 6: GAXRD patterns of an uncoated Si substrate and a 25-nm-thick ITO layer deposited by the BKM fabrication flow on a 12" Si wafer. Below is the corresponding pattern of a randomly oriented In_2O_3 powder exhibiting a cubic crystalline structure typical for rare-earth oxides.

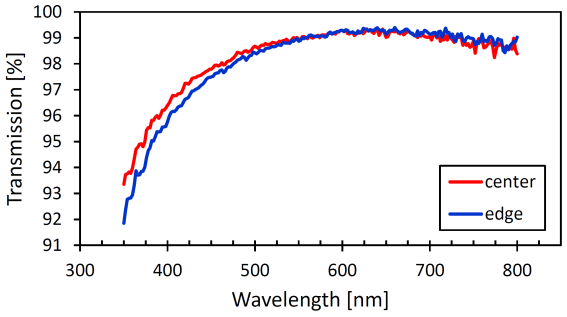

Figure 7: Optical transmission versus wavelength of a 25-nm-thick ITO layer deposited by the BKM fabrication flow on 2" Sapphire wafers fixed in the center (red) and at the edge (blue) of a 12" Si/SiO_2. wafer. The transmission was corrected for the attenuation of the 0.5 mm thick Sapphire substrate.

Furthermore, the resistivity distribution of the 25-nm-thick ITO layer deposited on the 12" wafer is presented in Figure 5. It was obtained from the measured thickness and sheet resistance distributions, and we observe that it exhibits a slight asymmetricity that could eventually be reduced or totally supressed by further optimizing the magnet array system and the process parameters in the high-pressure degasser.

Microstructure

During process optimization our goal was to produce ITO thin films with a (222) fiber texture, since it is known that this crystallographic orientation correlates with high Sn^{4+} doping efficiency, high transmission, high energy bandgap and high carrier mobility [17]. Basically, this required the use of relatively low sputter voltage and growth rates, as otherwise the more resistant oxygen deficient (400)-oriented grains would have been favored [18].

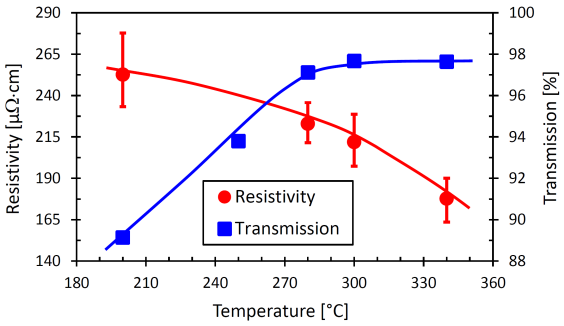

Figure 8: Average resistivity and optical transmission at 450 nm of a 25-nm-thick ITO layer deposited on 12" Si/SiO_2. and 2" Sapphire wafers versus post-annealing temperature.

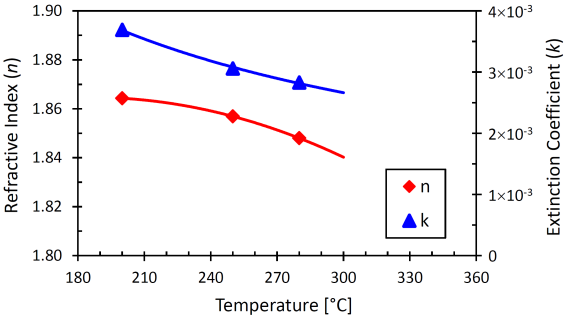

Figure 9: Refractive index and extinction coefficient of a 25-nm-thick ITO layer deposited on a 12" Si wafer versus post-annealing temperature.

Figure 6 shows the GAXRD pattern for a 25-nm-thick ITO layer grown on a 12" Si wafer using the BKM fabrication flow (post-annealing temperature and time were 300 °C and 60 s). For comparison the GAXRD pattern of an uncoated substrate is also presented together with the corresponding pattern of a randomly oriented In_2O_3 powder exhibiting a cubic crystalline structure characteristic for the rare-earth oxides. Thus, the pattern corresponding to the ITO thin film could be indexed by the cubic bixbyite structure (e.g., C-type, rare earth sesquioxide structure, Ia3 space group) of In_2O_3, which is the typical structure of the ITO material [19]. This suggests that most In atoms are uniformly substituted by the Sn atoms in the lattice [20]. Moreover, quantitative analysis of the diffraction peaks revealed that the ITO thin film exhibited mainly a (222) texture, and this particular reflection corresponding to a Bragg angle

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$2\theta = 30.3°$ was $\sim$ 400% more pronounced than that of a randomly oriented In_2O_3 powder.

Last but not least, by applying the Williamson-Hall analysis to the GAXRD pattern in Figure 6 we estimated the average grain size of the ITO film in the vertical direction as $\sim$ 8.5 nm. This is in agreement with results published by O. Tuna et al. who reported a grain size of 7.5 nm for 70-nm-thick ITO thin films deposited by DC magnetron sputtering and annealed at 300 °C [21].

Optical Properties

To assess the optical performance of the 25-nm-thick ITO layers we coated two 2" Sapphire wafers that were fixed onto a 12" Si/SiO_2 wafer in the center and edge, respectively. The optical transmission corrected for the attenuation of the 0.5-mm-thick Sapphire substrate is shown in Figure 7 for wavelengths between 350 and 800 nm. The measurements revealed a high transmission over the whole visible spectra with a steep decrease below 400 nm, which is attributed to the absorption of the photons with energy greater than the band gap of ITO, e.g., $\sim$ 3.7 eV, corresponding to wavelengths below 335 nm [22].

The effect of post-annealing temperature on optical and electrical performance of 25-nm-thick ITO layers deposited with the BKM fabrication flow is presented in Figure 8, depicting the optical transmission in the center of the wafer for a wavelength of 450 nm and the corresponding resistivity averaged over the whole 12" wafer versus the post-annealing temperature. Thus, the transmission gradually increases up to a $\sim$ 280 °C, and above this temperature it saturates to a value of $\sim$ 98%. Moreover, the resistivity still exhibits a gradual decrease even for temperatures above 280 °C.

Figure 9 shows the temperature dependence of refractive index n and extinction coefficient k[1] at 450 nm for a 25-nm-thick ITO layer deposited on a 12" Si wafer. It reveals that n decreases very slowly with the post-annealing temperature (e.g., 0.8% when temperature increases from 200 °C to 280 °C), whereas k decrease is more prominent (e.g., 23.4%).

Table 1 summarizes the performance of the 25-nm-thick ITO films deposited in an industrial CLUSTERLINE® 300E magnetron sputtering system, where U is the thickness uniformity, R_s the sheet resistance, R_s U the sheet resistance uniformity, ρ the resistivity, T the optical transmission at 450 nm, and R_a and R_{pv} are the absolute and peak-to-value roughnesses.

Table 1: Performance of 25-nm-thick ITO films deposited on 12" Si and Si/SiO_2. wafers in a Clusterline® 300E magnetron sputtering system using the BKM fabrication flow

U	R_s	R_s U	ρ	T	R_a	R_{pv}
[%]	[Ω/sq]	[%]	[μΩ cm]	[%]	[nm]	[nm]
2.8	68.2	3.4	171.7	97.7	0.1	2.3

Conclusions

We optimized the ITO deposition process on 12" Si and Si/SiO_2 wafers in an industrial CLUSTERLINE® 300E magnetron sputtering system. The optical and electrical properties of our ultra-thin ITO thin films set a new benchmark of quality for cost-effective manufacturing of transparent conductive layers on 300 mm CMOS, and can therefore help manufacturers meet exacting standards for next generation display technologies.

Acknowledgment

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[1] When light passes through a material (in this case the ITO layer), some part of it is attenuated. This effect can be taken into account by defining a complex refractive index $\underline{n} = n + ik$, where the real part n is the refractive index that indicates the phase velocity of the light propagating through the ITO material, whereas the imaginary part k is the extinction coefficient that reveals the corresponding attenuation upon light propagation [23].

References

[1] A. Stadler, Transparent conducting oxides: An up-to-date overview„ *Materials*, vol. 5, 2012, pp. 661–683.

[2] Z.B. Wang, M.G. Helander and Z.H. Lu, Transparent conducting thin films for OLEDs, in *Woodhead Publishing Series in Electronic and Optical Materials, Organic light-emitting diodes (OLEDs)*, Ed. Alastair Buckley, Woodhead Publishing Oxford, 2013, pp. 49–76.

[3] A. Morag and R. Jelinek, "Bottom-up" transparent electrodes, *J. Colloid Interface Sci.*, vol. 482, 2016, pp. 267–289.

[4] J. Peddie, *Augmented reality: Where we will all live*, 1st ed., J. Peddie Research Inc., Springer International Publishing, 2017, pp. 183–254.

[5] C. Griffin et al., Micro-pixellated flip-chip InGaN and AlInGaN light-emitting diodes, *Proc. Conf. Lasers Electro-Opt.*, Baltimore, MD, USA, 2007, pp. 1–2.

[6] Z.J. Liu, K.M. Wong, C.W. Keung, C.W. Tang, K.M. Lau, Monolithic LED microdisplays on active matrix substrate using flip-chip technology, *IEEE J. Sel. Topics Quantum Electron.*, vol. 15, no. 4, 2009, pp. 1298–1302.

[7] J. Herrnsdorf et al., Active-matrix GaN micro light-emitting diode display with unprecedented brightness, *IEEE Trans. Electron. Devices*, vol. 62, no. 2, 2015, pp. 1918–1925.

[8] B.R. Tull et al., High brightness, emissive microdisplays by integration of III-V LEDs with thin film silicon transistors, *SID Int. Symp. Dig. Tec.*, vol. 46, 2015, pp. 375–377.

[9] H.V. Han et al., Resonant-enhanced full-color emission of quantum-dot-based micro LED display technology, *Optics Express*, vol. 23, no. 25, 2015, pp. 244116/1–12.

[10] J.R. Bonar, G.J. Valentine, Z. Gong, J. Small, S. Gorton, High-brightness low-power consumption microLED arrays, *Proc. SPIE*, vol. 9768, 2016, 97680Y.

[11] W. Henry and C. Percival, ILED displays: Next generation display technology, *SID Int. Symp. Dig. Tec.*, vol. 47, 2016, pp. 747–750.

[12] R. Benz, MicroLED — Challenges for a new LED panel technology, *LAYERS*, vol. 3, 2017–2018, pp. 70–73, `https://issuu.com/evatec/docs`

[13] Y.H. Tak, K.B. Kim, H.G. Park, K.H. Lee, J.R. Lee, Criteria for ITO (indium-tin-oxide) thin film as the bottom electrode of an organic light emitting diode, *Thin Sol. Films*, vol. 411, 2002, pp. 12–16.

[14] `https://www.evatecnet.com/products/clusterline-platforms`

[15] Y. Miao et al., On the microstructure and strengthening mechanism in oxide disper sion-strengthened 316 steel: A coordinated electron microscopy, atom probe tomography and in situ synchrotron tensile investigation, *Mater. Sci. Eng. A*, vol. 639, 2015, pp. 585–596.

[16] G.K. Williamson and W.H. Hall, X-ray line broadening from filed aluminum and wolfram, *Acta Metall.*, vol. 1, 1953, pp. 22–31.

[17] E. Terzini, P. Thilakan, C. Minarini, Properties of ITO thin films deposited by RF magnetron sputtering at elevated substrate temperature, *Mater. Sci. Eng. B*, vol. 77, 2000, pp. 110–114.

[18] P. Thilakan, J. Kumar, Studies on the preferred orientation changes and its influenced properties on ITO thin films, *Vacuum*, vol. 48, 1997, pp. 463–466.

[19] A. Kulkarni, K.H. Schulz, T. Lim, M. Khan, Dependence of the sheet resistance of indium-tin-oxide thin films on grain size and grain orientation determined from X-ray diffraction techniques, *Thin Sol. Films*, vol. 345, 1999, pp. 273–277.

[20] N. Nadaud, N. Lequeux, M. Nanot, J. Jové, T. Roisnel, TStructural studies of tin-foped indium oxide (ITO) and $In_4Sn_3O_{12}$, *J. Sol. State Chem.*, vol. 135, 1998, SC977613, pp. 140–148.

[21] O. Tuna, Y. Selamet, G. Aygun, L. Ozyuzer, High quality ITO thin films grown by DC and RF sputtering without oxygen, *J. Phys. D: Appl. Phys.*, vol. 43, 2010, 055402, pp. 1–7.

[22] A. Klein et al., Transparent conducting oxides for photovoltaics: Manipulation of Fermi level, work function and energy band alignment, *Materials*, vol. 3, 2010, pp. 4892–4914.

[23] E. Hecht, *Optics*, 4th ed., Addison-Wesley, San Francisco, 2002, pp. 113–121.

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Technologies in Applications

432 The Dark Side of Light: Effects of Light Pollution on Insects and Agriculture
by Dr. Maja Grubisic, Leibniz-Institute IGB

438 LEDs Solutions for Sports Lighting
by Dr. Shih Shun Chang, Lumileds

446 Dynamic Lighting Technology
by Noe Bory, Insolight

450 Plants' Responds to Exposure of Different Lighting Conditions
by DI Volkmar Keuter, Fraunhofer-Institute for Environmental, Safety and Energy Technologies UMSICHT

456 Closed Loop Control Systems for Supplementary Lighting in Smart Greenhouses
by Dr. Viktor Zseller, ARROW Electronics EMEA

464 Universal LED Tubes: Detailed Descriptions of Design, Technologies and Market
by Dr. Martijn Dekker, Seaborough

470 Water Metering Data Acquisition and Transmission Through Street Lighting Enabled Network
by Arturo Rubio, ELT

478 Luminaire Efficiency | A Proposal to Think Different
by Andreas Niederstätter, Swareflex

The Dark Side of Light: Effects of Light Pollution on Insects and Agriculture

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Abstract

In recent decades, the use of artificial illumination has rapidly increased, transforming nocturnal environments worldwide. Inappropriate and extensive use of artificial illumination results in light pollution: an increase in nocturnal light above natural levels and a disruption of natural light cycles. Light/dark cycles have been stable over geological and evolutionary timescales, and most organisms rely on light as information source to regulate internal processes through circadian clocks. Furthermore, many organisms evolved to be nightactive, to perform their activities in what are naturally dark and dim night environments. Today, as almost a quarter of Earth's land experience light pollution, this novel, pervasive and widespread environmental change raises concerns about potentially adverse effects on organisms and processes in nocturnally lit ecosystems. As mounting evidence shows that artificial light at night affects microorganisms, plants, animals and humans, light pollution is increasingly recognized as a global concern and a threat to biodiversity.

Here, we give an overview of the recent research into ecological effects of artificial light at night with focus on insects, and discuss how various lethal and sublethal impacts of artificial illumination can increase environmental pressure on insect populations and threaten their survival. Alarming rates of declines in insect populations have been increasingly reported, including observations from lightpolluted areas. The role of artificial illumination in these negative trends needs to be considered in order to mitigate its adverse effects and allow for recovery of insect fauna in our landscapes.

Insects play important ecological roles in nature, and they are of key importance in agricultural ecosystems where they provide vital ecosystem services such as crop pollination and natural pest control. Therefore, negative impacts of light pollution on insects may have important consequences for agricultural production. By changing composition of insect communities and interfering with predatorprey interactions, artificial light at night may alter balance of species interactions and energy flows in the agroecosystem. Simultaneously, artificial illumination can directly influence physiology and productivity of crop species in its surrounding. How these impacts at different ecosystem levels interact to influence crop production and biodiversity is still not clear, and urgently requires attention given the importance of agriculture for humanity and a large potential for unintended impacts of artificial illumination.

While artificial illumination undoubtedly provides benefits to humanity, it often has negative unintended impacts on our environment.

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Ecological effects of light pollution are complex, but there is a large potential to mitigate these by developing technological solutions and lighting schemes and strategies. It is only in close collaboration with lighting industry, engineers, planners and designers that we can create and implement adequate solutions to reduce adverse ecological effects of light pollution.

Introduction

Artificial lighting has become an integral part of the modern world, exposing organisms and ecosystems to artificial light at night (ALAN) worldwide and raising concerns about potentially negative effects on ecology and human health. Until recently, light has been typically present during the day in most places on Earth, while nights were characterized by darkness and dim light from moon and stars. Now, widely present electrical lights are introducing light at times and places where it does not naturally occur; of intensities and quality that differs from those of natural light. Lights associated with urban structures, industry and transport networks, such as building exterior and interior lighting, security lights and street lights, are thus imposing dramatic changes to nocturnal environments and their inhabitants. Increase in nocturnal light levels and interruption of natural light/dark cycles that results from use of artificial light sources is commonly referred to as light pollution.

Light pollution has become widespread in the recent decades, with the spread of electrical lighting and increasing urbanization. Both direct and indirect light contribute to light pollution, and while presence of direct light is limited to relatively small areas around light sources, indirect light, or skyglow, light scattered in the atmosphere, spreads over much larger areas, tens and hundreds of kilometers from its source. It is mainly due to skyglow that as much as 23% of the world's non-polar land surface experience light pollution today[1], 1, making light pollution a global environmental and ecological concern of the 21st century.

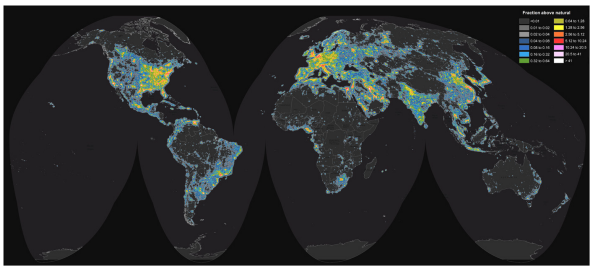

Figure 1: World map of artificial sky brightness (showed as a ratio to the natural sky brightness). Reprinted from [1].

Importance of light in nature and issues associated with artificial light at night

Light is an important cue in nature. Even at very low intensities, nocturnal light is utilized by night-active animals as a visual cue for orientation, navigation, predator avoidance, search for food and mates, and reproductive activities. A large amount of biodiversity — more than 30% of vertebrates and 60% invertebrates, including more than half of over 900 thousand known species of insects — evolved to be active at night [2]. These organisms are extremely sensitive to light, being adapted to perform their activities in dark or dim nights under illumination of moon and stars, on which many rely for movements across landscapes [3]. Moreover, as a non-visual cue, light regulates biological rhythms in almost all life on Earth. Regular diel and seasonal light/dark cycles have been stable and predictable through long periods of time, and many organisms evolved sensitive receptors to detect changes in light intensity, duration and spectral composition associated with these cycles. Light thus provides information about the external environment, allowing for synchronization of many physiological processes and activities with certain time of the day or period of the year. By disrupting natural light patterns, masking natural cues and providing misleading information, ALAN can thus interfere with visual perception and biological rhythms to disrupt natural behavior and activities of nocturnal insects [4]. How this affects insect populations in illuminated ecosystems is still not clear.

Effects of artificial light at night on insects

Effects of ALAN have been mostly studied under direct illumination, while much remains unknown on potential effects of indirect light on organisms and processes in illuminated ecosystems.

The most apparent and well-known effect is attraction of insects to artificial lights [5]. This can increase insect mortality, as insects often die in direct contact with the lamp, or stay trapped flying around the lamps until they die of exhaustion. Insects are strongly attracted to short wavelength lights, especially between 300 and 450 nm [6]); therefore lamps with high UV and blue light

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emission such as mercury-vapor and cool-white LEDs are highly attractive to large numbers and diversity of insect species, at distances of up to 130 m [7]. However, many sub-lethal effects of ALAN have also been demonstrated, including disruption of pheromone production [8], mating, feeding [9] and communication in moths, fireflies [10] and fruit flies [11]. These can reduce insect survival and population growth, potentially threating the stability of their populations over time.

ALAN induces changes in behavior of nocturnal insects and arthropods, often with species —and seasonally— specific patterns. While some predatory species, e.g., spiders, may benefit from large numbers of flying prey that aggregates around the lights, other species may avoid illuminated areas to prevent being eaten by visual predators. These changes can alter species abundances and the composition of insect communities [12], [13]. Consequences of such profound changes to ecosystems functioning in illuminated areas remain to be determined.

Insect populations have been declining at alarming rates over the last decades in many countries, including Germany [14]. While agricultural intensification, habitat destruction and fragmentation and use of pesticides are commonly recognized as drivers of these negative trends, ALAN is often overlooked as a potentially contributing factor, despite its numerous negative impacts on insects and presence in areas where declines have been reported [4]. ALAN often co-occurs with other urban stressors, and through many demonstrated lethal and sub-lethal impacts it could increase the pressure on insect populations in illuminated areas. Recent correlative studies provided the first links between declines in moth populations and light pollution [15], [16]. Given the important ecological roles insects play in nature, including key ecosystems services they provide to agriculture, declines in insect populations can have serious consequences for maintenance of these functions. The contribution of light pollution to declines in insects needs to be better understood and acknowledged, in order to mitigate its adverse effects and help recovery of insect fauna as well as maintenance of their vital ecological roles.

Figure 2: Rows of streetlamps act as barrier for movement of insects across landscapes, increasing habitat fragmentation in already fragmented agricultural areas, which reduces resilience of insect populations. Photo: M. Grubisic.

Insects and light pollution in agricultural ecosystems

Despite modern technological advances, agricultural production still largely depends on natural processes, including those provided by insects. Insects contribute to nutrient cycling, soil fertility, natural pest control and pollination in agroecosystems, so ALAN-induced changes may have important consequences for these ecosystem functions. Agricultural areas cover 11% of Earth's land and are often exposed to direct and indirect ALAN from street lighting and skyglow from nearby cities and suburban areas. Effects of ALAN, however, are yet to be systematically studied.

Agricultural landscapes are highly fragmented, with small natural habitats embedded in large areas that are intensively managed. In these habitats, dispersal capabilities play an important role. For nocturnal insects, rows of streetlights can form barriers, blocking movements and dispersal and enhancing the impact of habitat fragmentation. This may result in reduced recolonization of isolated habitat patches and ultimately in less resilient insect populations. As some species benefit from nocturnal illumination, e.g., visual predators, while others suffer from it, the insect community can also change as a result of ALAN and shift predator-prey and host-parasitoid interactions. The ultimate outcome of these impacts on both crop production and biodiversity are currently unknown, however given the importance of insects in agricultural ecosystems and the potential influence ALAN has, it is important that this will be quantified and possibly mitigated [4].

Options for reducing negative effects of light pollution

Currently, a shift in outdoor lighting technologies from traditional light sources to white LED lamps is taking place in many regions of the world with the aim of reducing energy consumption. This shift is, however, increasing illumination levels through rebound effects driven by increased use of LED illumination due to its lower costs [17]. To reduce negative impacts of artificial lighting it is necessary to adjust the intensity of light sources to their purpose and avoid illumination at places and times when it is not needed. By applying shields and adequate lamp designs, light can be directed to where it is needed to minimize glare, light trespass and skyglow. Furthermore, given the flexibility of LED technology and differential spectral sensitivity of wildlife, the spectral composition of light can be tuned to minimize unintended ecological effects. Blue-rich LEDs attract the highest numbers and diversity of insects, and are also known to influence birds, bats, plants and humans. Therefore reducing the output of harmful blue wavelengths is a promising approach to mitigation of negative ecological impacts of nocturnal illumination. The use of dimmers, timers and motion sensors can further reduce nocturnal illumination levels and unnecessary illumination in rural and sub-urban areas. By applying novel indices based on ecological, physiological and astronomical effects, the impacts of new light sources can be calculated and predicted based on their spectral composition [18]. All these approaches have a large potential to develop smart solutions and lighting policies to reduce and minimize adverse effects of light pollution, while still having adequate illumination when it is needed.

Conclusions

The widespread and increasing use of artificial lighting is increasing nocturnal light levels and disrupting natural light patterns in many regions of the world, raising concerns about ecological impacts of these unprecedented environmental changes. ALAN has numerous negative effects on insects and increases environmental pressure on their populations in large areas that are affected by light pollution, thereby potentially contributing to ongoing insect declines. It is necessary to recognize the importance of ALAN as a potential threat to insect populations and the need for developing smart solutions and adequate mitigation strategies in order to minimize these adverse effects and help recovery insect populations and their services in our landscapes.

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References

[1] F. Falchi, P. Cinzano, D. Duriscoe, C. C. M. Kyba, C. D. Elvidge, K. Baugh, B. A. Portnov, N. A. Rybnikova, R. Furgoni, The new World Atlas of artificial night sky brightness. Science Advances, 2016, 2, p. e1600377.

[2] F. Hölker, C. Wolter, E. K. Perkin, K. Tockner, Light pollution as a biodiversity threat. Trends in Ecology & Evolution, 2010, 25, pp. 681–682.

[3] J. J. Foster, J. Smolka, D. E. Nilsson, M. Dacke, How animals follow the stars. Proceedings of the Royal Society B-Biological Sciences, 2018, 285, p. 20172322.

[4] M. Grubisic, R. H. A. van Grunsven, C. C. M. Kyba, A. Manfrin, F. Hölker, Insect declines and agroecosystems: does light pollution matter? Annals of Applied Biology, 2018, doi: 10.1111/aab.12440.

[5] G. Eisenbeis, Artificial night lighting and insects: Attraction of insects to streetlamps in a rural setting in Germany, in Ecological consequences of artificial night lighting, C. Rich & T. Longcore Eds. Washington, D.C.: Island Press, 2006, pp. 281–304.

[6] M. Donners, R.H.A. van Grunsven, D. Groenendijk, F. van Langevelde, J.W. Bikker, T. Longcore, E. Veenendaal, Colors of attraction: Modeling insect flight to light behavior. Journal of Experimental Zoology Part A: Ecological and Integrative Physiology, 2018. doi: 10.1002/jez.2188

[7] T. Degen, O. Mitesser, E. K. Perkin, N.-S. Weiß, M. Oehlert, E. Mattig, F. Hölker, Street lighting: Sex-independent impacts on moth movement, Journal of Animal Ecology, 2016, 85, pp. 1352–1360.

[8] K. G. van Geffen, A. T. Groot, R. H. A. van Grunsven, M. Donners, F. Berendse, E. M. Veenendaal, Artificial night lighting disrupts sex pheromone in a noctuid moth. Ecological Entomology, 2015, 40, pp. 401–408.

[9] F. van Langevelde, R. H. A. van Grunsven, E. M. Veenendaal, T. P. M. Fijen, Artificial night lighting inhibits feeding in moths. Biology Letters, 2017, 13, p. 20160874.

[10] A. Firebaugh, K. J. Haynes Experimental tests of light-pollution impacts on nocturnal insect courtship and dispersal. Oecologia, 2016, 182, pp. 1203–1211.

[11] K. McLay, M. P. Green, T. M. Jones Chronic exposure to dim artificial light at night decreases fecundity and adult survival in Drosophila melanogaster. Journal of Insect Physiology, 2017, 100, pp. 15–20.

[12] A. Manfrin, G. Singer, S. Larsen, N. Weiß, R. H. A. van Grunsven, N.-S. Weiß, S. Wohlfahrt, M. T. Monaghan, F. Hölker, Artificial light at night affects organism flux across ecosystem boundaries and drives community structure in the recipient ecosystem. Frontiers in Environmental Science, 2017, 5:61.

[13] L. A. Meyer, S. M. P. Sullivan Bright lights, big city: Influences of ecological light pollution on reciprocal stream-riparian invertebrate fluxes. Ecological Applications, 2013, 23, pp. 1322–1330.

[14] C. A. Hallmann, M. Sorg, E. Jongejans, H. Siepel, N. Hofland, H. Schwan, W. Stenmans, A. Müller, H. Sumser, T. Hörren, D. Goulson, H. de Kroon, More than 75 percent decline over 27 years in total flying insect biomass in protected areas. Plos One, 2017, 12(19), p. e0185809.

[15] F. van Langevelde, M. Braamburg-Annegarn, M. E. Huigens, R. Groendijk, O. Poitevin, J. R. van Deijk, W. N. Ellis, R. H. A. van Grunsven, R. de Vos, R. A. Vos, M. Franzén, M. F. WallisDeVries, Declines in moth populations stress the need for conserving dark nights. Global Change Biology, 2017, 24, pp. 925–932.

[16] J. F. Wilson, D. Baker, J. Cheney, M. Cook, M. Ellis, R. Freestone, D. Gardner, G. Geen, R. Hemming, D. Hodgers, S. Howarth, A. Jupp, N. Lowe, S. Orridge, M. Shaw, B. Smith, A. Turner, H. Young, A role for artificial night-time lighting in long-term changes in populations of 100 widespread macro-moths in UK and Ireland: A citizen-science study. Journal of Insect Conservation, 2018, 2(22), pp. 189—196.

[17] C. C. M. Kyba, T. Kuester, A. S. de Miguel, K. Baugh, A. Jechow, F. Hölker, J. Bennie, C. D. Elvidge, K. J. Gaston, L. Guanter, Artificially lit surface of Earth at night increasing in radiance and extent. Science Advances, 2017, 3, p. e1701528.

[18] T. Longcore, A. Rodríguez, B. Witherington, J. F. Penniman, L. Herf, M. Herf, Rapid assessment of lamp spectrum to quantify ecological effects of light at night. Journal of Experimental Zoology, Part A: Ecological and Integrative Physiology, 2018, doi: 10.1002/jez.2184.

LEDs Solutions for Sports Lighting

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Abstract

This paper discusses how spectral tuning and LED source size can be used across all sports lighting applications.

In years past, the retrofit lamp industry witnessed the revolution of indoor lighting migrating from low CRI bulbs to now 90 CRI bulbs due to advancements in die and phosphor efficiency as well as color rendering technology. The sports lighting industry is experiencing a similar phenomenon; however, sports lighting have an added complexity where high end sports lighting not only serve a human audience, but also a silicon detector; hence, requiring TLCI values greater than 90, in addition to fulfilling CCT/CRI specifications on lighting. The high TLCI values can be achieve by intelligently color tuning with phosphors.

This paper shall explain the vast field of sports lighting requirements from the lights at a primary school's gymnasium to the local neighborhood sports field to professional stadiums where championship games such as the Super Bowl and World Cup are held and televised. The added dimension of televising places a requirement on TLCI. We shall analyze the differing color perceptions when broadcasting cameras film under low or high TLCI lighting.

In addition, we shall examine the new sports lighting specifications from China as well as review the IES recommendations on sports lighting and how NEMA beam types are used to achieve the appropriate light distribution.

As the optical radiation pattern for sports lighting tend to be narrow, the optical source size of the LED will impact the size of the lens and consequently the size of the fixture. An example will be given on how a big LED is at a disadvantage to a smaller LED with high brightness.

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Introduction

Sports lighting for broadcasting is an exciting field where the light needs to satisfy not only humans, but also sensors in CCD cameras. In LpS 2017 [1], authors discussed spectral tuning using LEDs and explained how the LED industry can provide high color gamut and fidelity lighting for the human observer. The authors briefly discussed light for the "machine" observer, specifically cameras used in broadcasting. These machines have a different sensitivity curve, when compared to the human eye response. Hence, when it comes to broadcast events with a live audience, lighting which fulfills the needs of the human eye response curve and the CCD camera response curve becomes crucial. The light not only need to be vibrant and please the human observer, but also have the correct spectral content to satisfy the machine observer to minimize any corrections.

This paper will examine sports lighting applications with LEDs. We will discuss and compare CRI and TLCI, the main metrics used to quantify light quality for humans and for CCD sensors, respectively. Not all sporting events require broadcasting; hence, we will present a breakdown of TLCI requirements by venue. Next, we shall examine TLCI requirements in another part of the world, China. China recently issued new specifications/recommendations for sports lighting. We will also discuss how customers can achieve high TLCI solutions through spectral tuning whether though phosphor converted LEDs or color mixed solutions. Finally, we will wrap up and discuss how LEDs can affect the optical beam pattern as well as the fixture size of the sports lighting luminaire.

Color Rendering Metrics CRI vs TLCI

For humans, CRI is the most popular metric for quantifying color rendition. As a refresher, CRI is calculated with 8 different pastel-like colors, referred to as R1-R8 in Figure 1.

CRI is reported in a scale from 0 to 100. Generally, users associate a higher CRI value with high light quality; however, this can be deceiving, as CRI does not report a deep blue or red component. For example, a tungsten lamp would have a CRI of 100; however, a tungsten lamp would not illuminate deep blue colors well. Because of weaknesses in the CRI calculation,

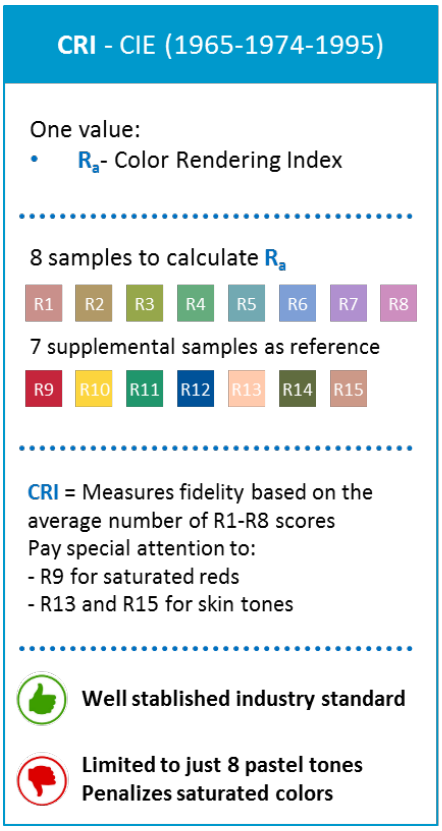

Figure 1: Colors used to calculate CRI.

many customers require not only a high CRI, but also a high R9 for red or high R13-R15 values for skin tones. Generally, light sources with high CRI and high R9 will provide humans with exceptional color rendering.

Unfortunately, for broadcasting, high CRI does not equate to a good light source for cameras. The censors in the camera detect wavelengths differently from the human eye. Figure 2 shows the eye sensitivities for a human and CMOS sensor, for example. Furthermore, there is a film emulsion, which also responds to light, thus complicating the issue even more; therefore, lighting for broadcasting must take into consideration the entire camera and display. This is where the metric TLCI comes in.

To account for the differences between the human eye response and the response to light for the camera and display, the European Broadcasting Union (EBU) introduced the Television Lighting Consistency Index (TLCI) to evaluate light that will interact with cameras. The EBU website states, "TLCI mimics a complete television camera and display, using only those specific features of cameras and displays which affect color performance, and increasingly more and more TV Studio (such as: BBC, CNN, NBC, iTV, Disney

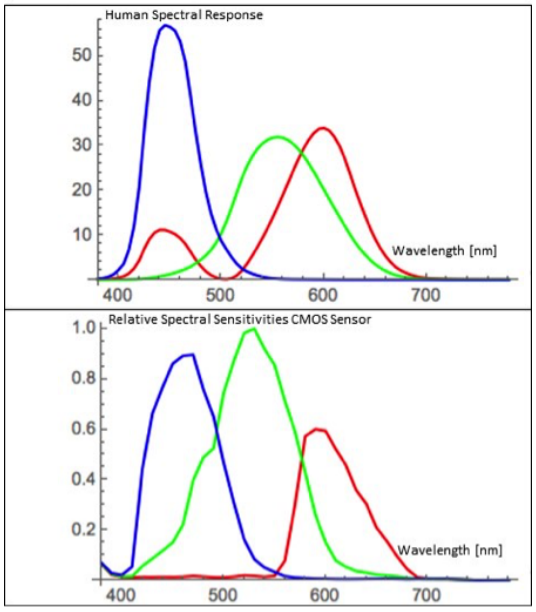

Figure 2: Comparison of human and CMOS spectral sensitivities.

CHANNEL. . .) are adopting TLCI as their standard when purchasing equipment."

While CRI is calculated from a standard consisting of 8 colors, TLCI is calculated from the colors of the MacBeth Color Checker, see Figure 3.

Figure 3: MacBeth Color Checker.

Just like CRI, TLCI compares the appearance of each color between the test light source and a reference perfect black body light source or daylight. The first row of the Color Checker contains natural colors meant to represent skin tone, the sky, and natural surroundings. The second row contain colors to represent a wide gamut range, while the third row consists of primary and secondary colors, such as blue, green, and red. The last row is a gray scale checker and is not used for color rendering calculations.

TLCI values also range from 0 to 100, with 100 being the best. Typically, TLCI is classified into 5 categories.

Five Categories of TLCI

- 85 $\rightarrow$ 100: Errors are so small that a colorist would not consider correcting them
- 75 $\rightarrow$ 85: A colorist would probably want to correct the color performance, but could easily get an acceptable result
- 50 $\rightarrow$ 75: A colorist would certainly want to correct the errors, and could probably achieve an acceptable result, but it would take significant time to get there
- 25 $\rightarrow$ 50: The color rendering is poor, and a good colorist would be needed to improve it, but the results would not be to broadcast standard
- 0 $\rightarrow$ 25: The color rendering is bad, and a colorist would struggle for a long time to improve it, and even then the results may not be acceptable for broadcast

Typically, $TLCI > 90$ is deemed broadcast quality with no need for correction.

Sports Field Venue Type

IES defines four classifications for various sports field types, as summarized in Figure 4.

IES RP6-15: Classification of Play

FACILITY	CLASS			
	I	II	III	IV
Professional	X			
College	X	X		
Semi-Professional	X	X		
Sports Clubs	X	X	X	
Amateaur Leagues		X	X	X
High School		X	X	X
Training Facilities			X	X
Elementary School				X
Receational Event				X
Social Event				X

Figure 4: IES suggested classifications for sporting venues.

The number of spectators attending the event defines the classifications, where:

Class I Competition play before a large group (5000 or more spectators).

Class II Competition play with facilities for up to 5000 spectators.

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Class III Competition play with facilities for up to 2,000 spectators.

Class IV Competition or recreational play at fields that do not draw a large number of spectators such as youth leagues that are typically only attended by family members of the participants.

For light rendering purposes, the classifications can be simplified as:

- Professional/Semi-professional/College — Events that are broadcast where attendance is $>$ 5000 spectators. As these events are broadcasted a TLCI $>$ 90 for the lighting is recommended. This reduces or eliminates the need for corrections of color during the broadcast. From a LED point of view, this generally corresponds to LEDs with CRI $>$ 90; however, LEDs with CRI $>$ 80, can also achieve high TLCI scores, if spectrally tuned.
- Semi-professional/College/Club — These are events attended by under 5000 spectators. Good color rendering is enhances the spectator's experience, but TV broadcasting is not a major consideration. From the LED point of view, CRI $>$ 80 is sufficient and this often produces TLCI scores $>$ 60
- Recreational/Amateur — This is typically the facilities in the neighborhood, for example, the local basketball court or swimming pool, as shown in Figure 5. In these arenas, the spectator or user needs to have sufficient light and color rendering. LEDs with a CRI $>$ 70 are often sufficient in these locations. In fact, as will be shown later, the recent recommendations from China, recommend a CRI $>$ 65 for these locations.

LEDs in Sports Lighting

If done properly, LEDs are an excellent solution for sports lighting. The spectral output of LED solutions can easily be optimized for color rendering. Alternatively, if efficacy is a concern, the LEDs can be optimized for high efficacy and still achieve CRI $>$ 70. LED solutions can come in the form of phosphor converted white light, or multi-colored solutions where the wavelengths are tuned for specific frequencies.

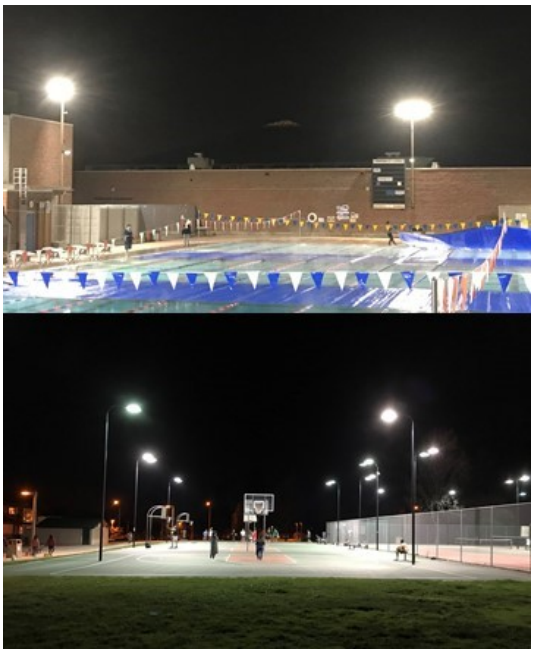

Figure 5: Neighborhood sports facilities in West San Jose, California.

Phosphor Converted White Light Solutions

The following are examples of LEDs that can meet the requirements of color rendering for the various venues.

Professional/Semi-professional/College

As discussed earlier, these events are often broadcasted, where high-speed cameras and slow motion replay are needed. TLCI $>$ 90 is recommended in these events to reduce or eliminate the need for color correction. Examples of spectra of LEDs meeting this requirement are found in Figure 6. Figure 7 show the results on the color chart between a reference illuminate and a LED with TLCI = 93. The spectra of the LED is also compared with the spectra of the illuminant. Very little, if any, discernable color difference can be seen between the two light sources.

Semi-professional/College/Club

Generally, a LED source with CRI $>$ r 80 is recommended for these applications. Figure 8 show the typical TLCI values for LEDs with CRI 80. Figure 9 show the differences in color rendition between a reference illuminant and a LED with TLCI = 67. Colors with

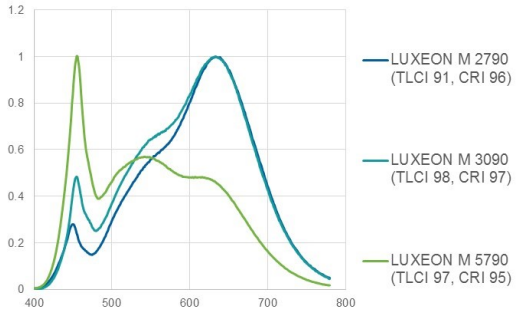

Figure 6: Examples of LED spectra with TLCI > 90.

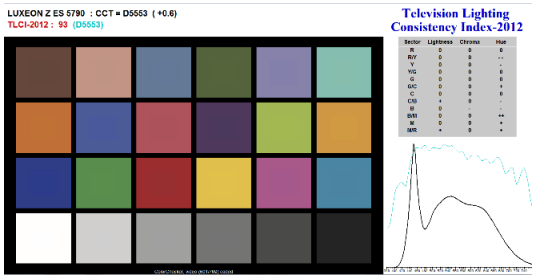

Figure 7: Color rendering results for a LED with TLCI > 90 compared to a reference illuminant.

red/orange/amber content are slightly different when compared to the reference illuminant.

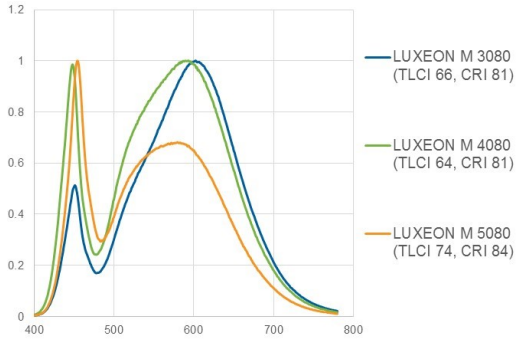

Figure 8: Typical TLCI values for LEDs with CRI > 80.

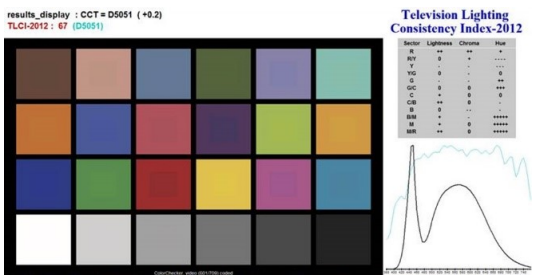

Figure 9: Comparison between a LED with TLCI = 67 and a reference illuminant. Slight variations are seen in colors with red, orange or amber content.

Recreational/Amateur

Lights for recreational users need to have good color rendition, but are not hampered by the need for broadcasting. Normally, LEDs with CRI > 70 are sufficient for these applications. Figure 10 shows the spectra for 70 CRI LEDs with various color temperatures. In this example, 70 CRI spectra yield a TLCI value greater than 50.

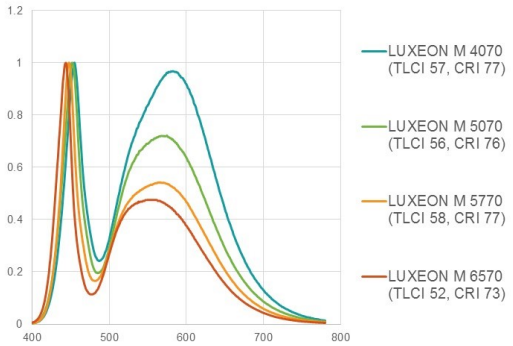

Figure 10: Typical spectra for CRI > 70 and its associated TLCI values.

Analysis of the spectra presented in Figures 6, 8, and 10 show that higher CRI LEDs have a fuller coverage over the visible wavelengths. For example, it is clear that the spectra for the 90 CRI LEDs have much broarder coverage in the amber to red regions. The closer the light source can mimic the spectra of the illuminant the higher the CRI and TLCI value.

Color Mixing for Spectral Tuning

The previous section discussed phosphor converted white light. However, white light can also be created by mixing individual colors. In fact, mixing colors allows the user to more fully match the spectra of the reference illuminate. For example, let's look at the result of mixing 7 LUXEON C color LEDs from royal blue to red. The specific part numbers and flux values are shown in Table 1. Figure 11 shows the resulting spectra of mix 7 different colors. The CRI for the resultant spectra is only 86. However, the TLCI is 96! Therefore, one can't assume that CRI < 90 cannot provide excellent TLCI. Furthermore, closer examination of the 90 CRI values also show that one cannot assume that LEDs with CRI above 90 will have superior TLCI values to LED solutions where the CRI is under 90.

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Table 1: Seven LUXEON C LEDs used for spectral mixing to re-create the spectrum of the illuminant source.

SPD#	Part Number	Color Bin	Phiv [lm]
1	L1C1-RYL1000000000 (Royal Blue)	50	6.3 (~174mW)
2	L1C1-BLU1000000000 (Blue)	40	6.4
3	L1C1-CYN1000000000 (Cyan)	30	15
4	L1C1-LME1000000000 (Lime)	10	153
5	L1C1-AMB1000000000 (Amber)	20	21
6	L1C1-GRN1000000000 (Green)	30	17.5
7	L1C1-RED1000000000 (Red)	40	21

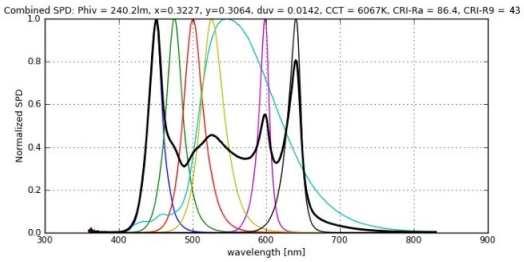

Figure 11: Resultant spectra of mixing 7 LUXEON C LEDs from royal blue to red.

Sports Lighting in China

Recently, China released document JGJ153-2016, Standard for Lighting Design and Test of Sports Venues. China delineates its sports venues by 3 categories of broadcasting: no broadcasting, TV broadcasting, and HDTV broadcasting, as shown in Table 2. However, for color rendering the Chinese requirement uses CRI and not TLCI. TLCI is mentioned in the standard, but no requirements are provided. Please see Table 3 for color rendering requirements.

Table 2: Summary of Chinese sports lighting classifications.

I: Gym, amateur training	No TV Broadcast
II: amateur game, professional training	
III: professional game	
IV: TV broadcast game	TV Broadcast
V: TV broadcast important game	
VI: HDTV broadcast game	HDTV Broadcast

Table 3: Summary of color rendering requirements by broadcast type.

	Ra	R9	CCT
No TV Broadcast	65	NA	4000K
TV Broadcast	80	0	4000K/ 5500K
HDTV Broadcast	90	20	5500K

While the Chinese standard does not specify TLCI, it does specify a beam angle requirement, which is the same as NEMA's beam angle requirement, and is explained in the next section.

LED Solutions for Sports Lighting

As discussed earlier, LEDs are an excellent choice for meeting the color rendering requirements of sports lighting. However, color rendering should not be the only specification under consideration. LED characteristics, such as color over angle (COA) and source size are important as well.

Color over angle describes how the CCT of the LED varies from different viewing angles. The COA is a result of LED design. As the blue light passes through the phosphor, the path of each blue light ray through the phosphor varies. Blue rays that travel through more phosphor will appear as a warmer color after the light exits the LED package, while blue rays traveling through the minimum phosphor thickness will appear color. If the phosphor coverage is poor, then in extreme situations, there will be non-converted blue light escaping the LED package. A comparison of COA for two different high power LEDs is shown in Figure 12. Both LEDs have the same die area and both LEDs are 4000 K and 70 CRI. The LUXEON V has a variation in color of roughly 500 K. The other LED has a color variation over 1300 K.

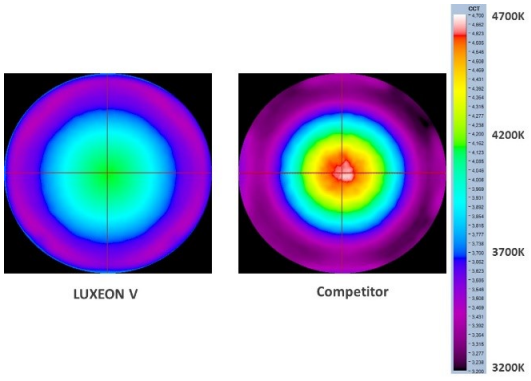

Figure 12: Comparison of color over angle between two high power LEDs with the same die area and color point (4000 K, 70 CRI).

Another important aspect in sports lighting is the beam angle. NEMA defines seven different angle types, which is now also utilized in the new Chinese standard. Selecting LEDs with a small light emitting surface area and high flux is critical in determining the size of the sports light fixtures.

For example, consider a fixture needing 100.000 lm with a maximum power dissipation of 750 W. Low flux LEDs would not be logical for use in this type of fixture, as too many LEDs are required. Hence, larger and higher power LEDs

Table 4: NEMA beam pattern types

NEMA Angle Types	
	Beam Angles [°]
Type 1	10–18
Type 2	18–29
Type 3	29–46
Type 4	46–70
Type 5	70–100
Type 6	100–130
Type 7	> 130

are required. However, while larger LEDs have more flux, it's disadvantage comes in its optical size. Let us compare the optical sizes needed for a 4 sqmm LED compared to an 8 sqmm LED.

Using Ledil's website (`www.ledil.com`), we can find approximate optics sizes for a 4 sqmm LED and an 8 sqmm LED. (The name of the competitor 8 sqmm LED has been covered.) The smaller LUXEON V LED needs an optics with a diameter of 16.1 mm, while the larger 8 sqmm LED needs an optics with a diameter of 35 mm, for a beam angle with a FWHM of $\sim 21°$, see Figure 13. In a system solution, roughly 10–11 of the larger 8 sqmm LED is equivalent to 25 LUXEON V LEDs. However, due to the larger optics for the 8 sqmm LED, the fixture size using the 8 sqmm LED is almost double the size if using the LUXEON V. Figure 14 shows a size comparison-using optics for 25 LUXEON V to 10 of the competitor 8 sqmm LED. Therefore, the right balance between LED size and flux output must be found to minimize the fixture area.

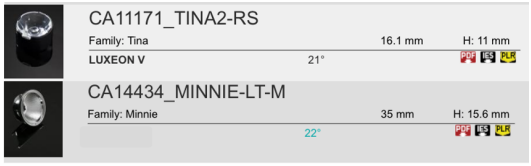

Figure 13: Optics sizes for LUXEON V compared to an 8 sqmm LED.

Conclusion

We have reviewed the various color rendering requirements for sports lighting. We have shown how LEDs can solve the color rendering requirements of TLCI. In addition, we have discussed how to select LEDs for sports lighting and given examples of color over angle as well as how LED source sized affects the size of the

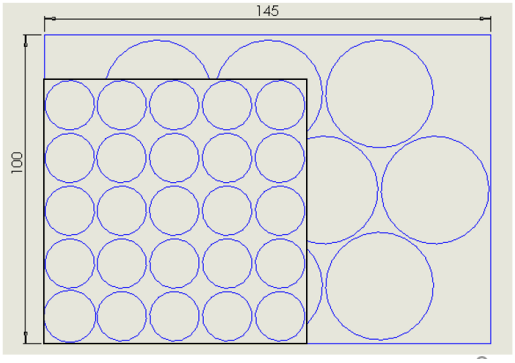

Figure 14: 25 LUXEON V LEDs with optics overlaid onto 10 competitor 8 sqmm LEDs with optics. The solution using LUXEON V will be almost 50% smaller in area.

optics. Choosing the right LED will give customers the best balance between color rendering, color over angle, and the area of the fixture.

References

[1] Sischka, I., & Chang, S. (2017). Opportunities in Spectral Tuning from High Color Rendition to Horticulture Applications. LpS 2017. Bregenz, Austria.

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Dynamic Lighting Technology

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Abstract

Through a patent-pending planar micro-tracking technology coming from solar applications, Insolight is developing an innovative dynamic luminaire technology, which allows to redirect light from a LED flat panel without tilt. The technology is based on a combination of different technology blocks: a custom optical layer and a microtracking system integrated into a LED module. By slightly shifting in the plane the LEDs compared to the optics, tis technology allows to control the output light beam and its direction. The tilt precision and the pan of the light beam can be remotely changed via a smartphone or typical control protocol (DALI/DMX). The optical system can be customized and optimized for any photometric curves, from a narrow beam to an asymmetric curve. This technology can be implemented in a wide range of luminaires, opening new applications for dynamic lighting in static luminaires.

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Introduction: a disruptive lighting technology from solar application

Insolight innovation is an optomechanical system, which has been originally developed for increasing the efficiency of solar panels.

The optomecanical system allows, in solar applications, to concentrate any incident sunlight on high efficiency solar cells positioned in a standard flat panel frame. By slightly moving the solar cells array compared to the optimized optics, the system is able to harvest sunlight during an entire day.

Reversing the optical path, and simply replacing the solar cells by LEDs, the system becomes a disruptive lighting technology. It can change the light orientation dynamically in an “invisible” manner. Thanks to the patent-pending planar optical micro-tracking technology, it becomes possible to generate various photometric curves in a LED flat panel, without any tilt.

Dynamic lighting technology from a flat panel

The light engine combines three different technology blocs:

- A LED module with an array of standard LEDs positioned over a PCB
- An optical arrangement able to capture a light beam from the LED array and redirect it with a given angle and associated photometric curve.
- A shifting mechanism (microtracking technology) that moves the optical arrangement to ± 10 mm in the x and y direction.

The optical layer

Insolight optical layer shape is optimized to create a set of specific photometric curves from a movement in x and y of the LED PCB, in Figure 1.

Insolight developed a optimization process (implemented in ZEMAX) to produce optimized optical shape for any set of targeted photometric curves.

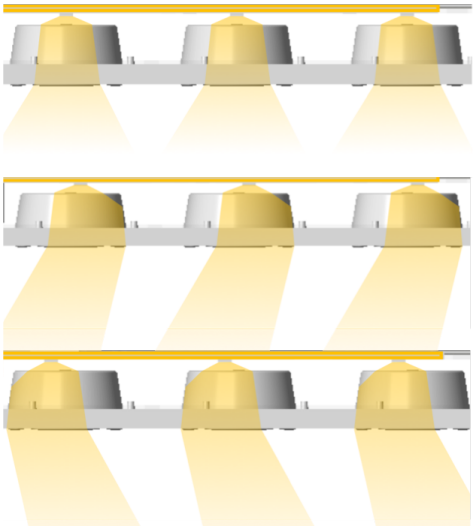

Figure 1: Multiple optical path in one optic based on the LED displacement.

From the study of a complex merit function and the targeted IES curves, the optimization process manages to create an optimal optical shape that converges the simulated IES curves to the targeted IES curves.

Figure 2 presents an example of photometric curves that can be obtained with a single optic.

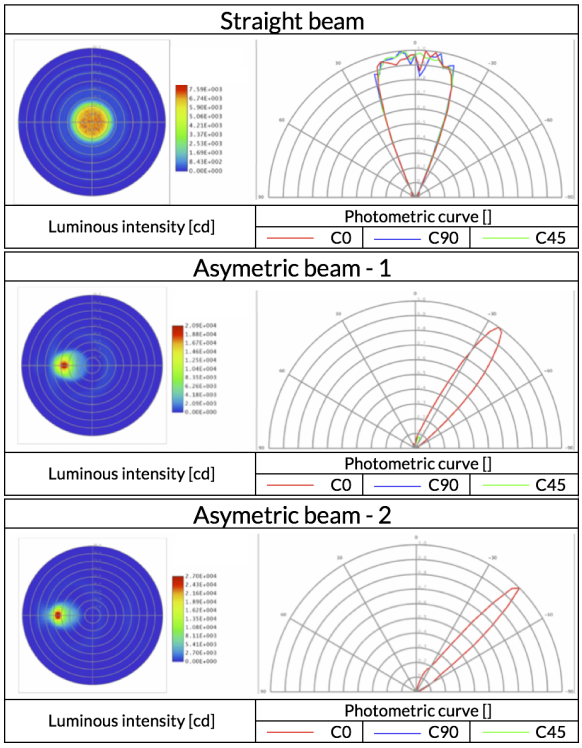

Figure 2: Example of IES curves obtained with a single optic.

The output of the process is an optimal optical shape and a LED displacement distance. The optical shape is used for the optics injection mold

and the LED displacement distance as a parameter for the micro tracking system.

The micro-tracking system

The guiding element (micro-tracking system) makes sure to move the optical layer compare to the LED PCB without any rotation and misalignment.

The system is a combination of a leaf-spring system and two actuators. The leaf-spring guiding system ensures a reliable displacement of the optical layer to the LED PCB while keeping a perfect parallelism. The actuators are integrated into the leaf-spring system to move the LED compare to the optical layer. The two actuators, positioned in the *x* and *y* direction push the leafs and create the bidirectional LED PCB movement. Then, actuators are connected to drivers allowing the movement to be controlled with DALI/DMX.

The leaf-spring guiding working principle is presented in Figure 3.

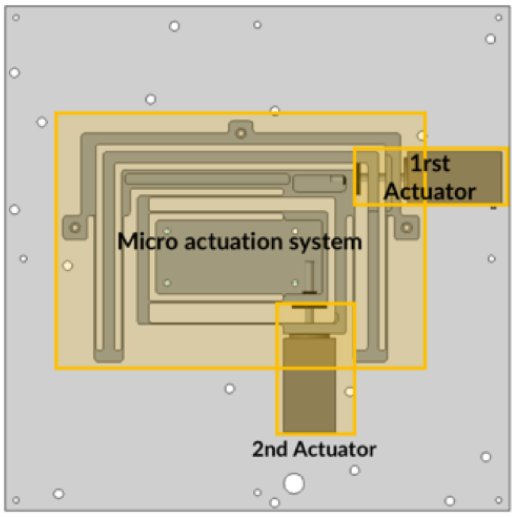

Figure 3: Leaf-spring system working principle.

The key advantages of using such system are:

- Movement: XY-translation between the optical elements and the LEDs
- No *z* rotation from design
- *xy* planarity from design
- Mechanical resistance, robustness and reliability
- Easily manufactured

The leaf-spring system is designed in order to be below the plastic limit of the material for any movements. The only failure mechanism is therefore fatigue, which is controlled with a finite element analysis, solver and mechanical simulation software, see Figure 4.

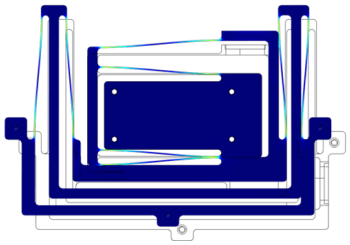

Figure 4: Leaf-spring system stress analysis.

A wide range of applications

Insolight know-how lies in the optics design optimization process and in the micro-tracking guiding system. The resulting module can be adapted for any applications and implemented in a wide range of luminaires. This can be used in various applications where modularity of the light output is desired.

Indoor lighting

Retail

The technology offers unlimited shop configurations, covering the entire store lighting needs with a single family of luminaires. The scenes can be freely rearranged with an app, without reorganization or refurbishment costs. With a perfect integration in the store, it is the slimmest adjustable LED panel on the market. No distraction are coming from the ceiling with a clean and small, unobtrusive design.

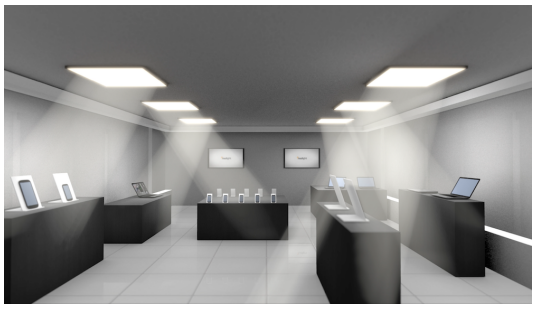

Figure 5: Insolight technology for retail applications.

Office

Insolight lighting technology offers unique multi-usage rooms: meeting room, celebrations presentations can be reunited in one single

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space. No refurbishment costs are needed, while maintaining optimized light utilization. The luminaire can also integrate a natural sunlight trajectory. Combined with a circadian cycle, it becomes a skylight window for a unique working atmosphere.

Figure 6: Insolight technology for Office applications.

Stage

The solution offers unique benefits compared to all other static stage lighting solutions, allowing multiple scenes with one single installation. It allows to switch from different scenes with few clicks on the app. Large motorized spot lights can be replaced by flat luminaires, nicely integrated and more reliable. Maintenance and installation set up are simplified, allowing savings on time and costs.

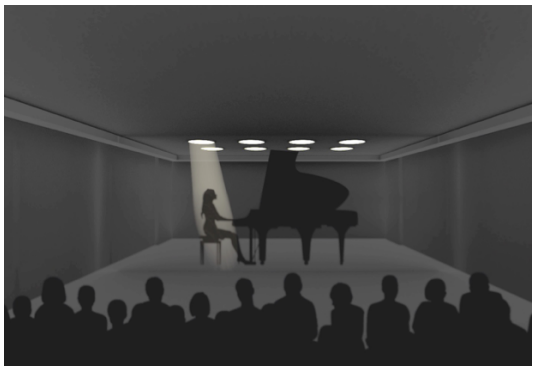

Figure 7: Insolight technology for stage application.

Outdoor lighting

Architecture

Insolight technology can be integrated architectural wall washers, for dynamic highlight of places, monuments or buildings. It offers unique light shows for cities, without a substantial costs difference compared to current static solutions. Unlike other adjustable wall washers, Insolight system is fully encapsulated, making it more reliable in an outdoor environment.

Street lighting

Integrated into road luminaires, Insolight technology can combine different photometric curves into a single luminaire used for different road lane arrangements. It allows major savings on tooling and product inventory costs and opens new perspectives for the future smart and connected cities.

Conclusion

Through its planar micro-tracking Technology, Insolight lighting technology offers dynamic beam steering and adaptative photometric curves for a low bill of material. The optimized optics guarantee a high optical efficiency while the micro-tracking system allows a reliable, rotation free and planar movement of the LED array with respect to the optics. This technology can be implemented in a wide range of luminaire (Indoor lighting, architectural lighting, outdoor lighting and technical lighting) and opens new integrations and new perspectives for dynamic lighting.

Plants' Responds to Exposure of Different Lighting Conditions

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Abstract

Photosynthesis of plants is a well-known physiological process in which for example chlorophyl is developed. correlation of Light influencing secondary plant substances, also known as phytochemicals, are less known. They are produced by special cell types in plants and do not belong to the vital substances, but nevertheless they fulfill important tasks, too, such as sun protection. Those phytochemicals seem to be of high value for the human health, for they are considered to be free radical interceptors. The following article addresses the light conditions necessary for the increase of these phytochemicals without affecting the plant growth.

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Introduction

Towards 2050 and beyond, Germany will face a huge number of challenges. Besides issues related to the aging of the population, transition to renewable energy sources and urbanization, on the food supply side the pressure of supplying fresh and high-quality food with a low environmental footprint will be a defining feature. Several studies suggest that, on the supply side, the challenges facing the developed world will lie primarily in maintaining high yields while reducing the environmental impact of the agricultural intensification practices that make those yields possible, achieving food security through sustainability.

Controlled environment agriculture (CEA) can be one option to grow food in urban areas as well as in harsh environments, cold climates and warm climates, irrespectively of the season. Limiting the dependency on favorable weather conditions will be a driver for the adoption of a new technology in agriculture.

LED grow lights as well as in combination with novel sensor technologies have the potential to gradually replace HPS lighting to increase yields and decrease resource consumption in traditional greenhouses and closed environments. Besides factors as energy efficiency and higher yields the use of LED grow lights offers the opportunity to address the control of plants' quality as for example primary and secondary plant metabolism by specific light regimes.

State of the art of technology and know-how

Plants absorb light as an energy source for cell growth. Furthermore, they use light as an important external signal for a wide range of physiological responses like the production of phenolic compounds, terpenoids and alkaloids. The interaction between light and plant metabolism is completely specific, therefore it is necessary to design specific studies for each species of interest and plant. LED technology has been used in horticulture for a few years. The biggest advantage of this technology is its ability to emit light of a specific wavelength. In plant applications, the effects of various wavelengths on the plant growth can be studied. Furthermore, it is possible to influence the forming of phytonutrients by the spectrum of light.

Chemical analysis of secondary plant metabolism

Flavonoids form one of the largest groups of secondary plant metabolites found in plants; approx. 6500 of them have been identified yet (Samanta et al. 2011 [1]). Anthocyanins and flavonols are two of the six subcategories. Secondary metabolites are not necessary for growth and development of the plants but, e.g., for the color and the flavour. Nevertheless, they do have important functions such as protecting the plant against harmful UV radiation. Additionally, they seem to have a great impact on human health. The production of anthocyanins and flavonols is depending on the illuminant. Dietary flavonoids are mainly found in their O-glycosidic form and are mostly analyzed by High Performance Liquid Chromatography (HPLC). The way of preparing the leaves to receive reproducible results is not trivial. To show how much of the anthocyanins and flavonols are produced under which light scenario, a standardized sample preparation has been developed.

LEDs for different grow applications

Secondary substances of plants are significantly influenced by several parameters, like, e.g., genotype, light conditions, environmental temperature, irrigation, fertilization and soil conditions (Pérez-Balibrea et al. 2008 [2], Mou 2009 [3], Tiwari et al. 2013 [4], Walters 2005 [5]). Many studies show an impact of light quality, light intensity and photoperiod on secondary plant metabolism and the content of beneficial (vitamins, soluble sugars, proteins, secondary antioxidants) and harmful (e.g., nitrate, oxalate acids) substances for human nutrition (Bian et al. 2014 [6]). The topic of the following section deals with the influence of light quality, i. e. spectral composition on phytochemical contents. Literature shows many cases where the impact of different light qualities on secondary substances is not stringent. Therefore, primarily results determined in various studies are presented.

Metabolites as for example carotenoids or anthocyanins, which are able to scavenge radicals, are known to play a considerable role for human nutrition. Different studies demonstrate various influences of exposure on the concentration of carotenoids. However, most of

them show different results depending on species and cultivars. For example, Lobiuc at al. reported a rise of the carotenoid concentration when illuminating green basil with blue and red LEDs with a ratio of 2:1, whereas the group of Dlugosz-Grochowska et al. showed the highest content of carotenoids in Lambs Lettuce using 30 % blue and 70 % red LED light (Dlugosz-Grochowska et al. 2017 [7]; Lobiuc et al. 2017 [8]).

For quite some time UV was thought to have negative effects on plants, but in recent years, the impact of short wavelengths beyond the VIS domain is investigated more and more. Garcia-Macias et al. [9] show an accumulation of phenolic compounds in tomato fruits and lettuce grown under UV (290–400 nm) radiation. At UV-ranges from 380–400 nm this effect decreases. Kim and Lee measured the highest content of anthocyanins in lettuce illuminated with blue and UV-B light [10]. UV-light not only shows a positive impact on the concentration of anthocyanins used as a sole source, but also in combination with blue or red light (Li and Kubota, 2009 [11], Goto et al., 2016 [12]). Negative effects of far-red light to anthocyanin content in potatoes are reported in 1998 (Yanovsky et al., 1998 [13]). Several studies consider blue and red light as important factors to increase the content of anthocyanin. This outcome is also shown in red leaf lettuce (Mizuno et al., 2009 [14]), green leaf lettuce (Samuoliene et al., 2012 [15]), and as pre harvest short-term exposure in broccoli, kale, parsley and pea (Samuoliene et al., 2010 [16]).

Beside the spectral composition, also the duration and repetition rate of illumination — the photoperiod — influence the accumulation of secondary metabolites. In the study of Kim and Lee, the best results considering the level of anthocyanins were obtained applying a light and dark ratio of 12/12 h.

Furthermore, the species itself appears to have a high influence on the effectiveness of the illumination.

Results

During the illumination phase, the plants are cultivated in climate chambers (ref. Figure 1) in which different LED modules have been installed. First experiments were carried out with six LED modules (type 1, ref. Figure 2) per chamber. Per

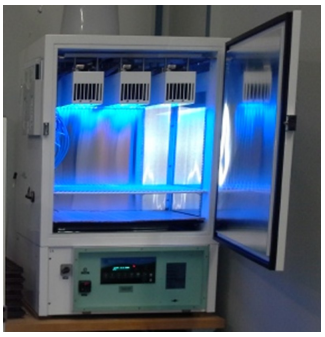

Figure 1: Climate chamber.

module 600 surface-mounted LEDs are mounted on a carrier board. The color channels are listed in Table 1 with corresponding wavelengths and photon flux densities (PPFD). The six channels can be controlled separately, so additive light compositions can be realized.

Figure 2: LED module.

Table 1: LED module (type 1).

Channel	Color	Wavelength (nm)	PPFD (µmol/(ms^2))
1	white 1	455 and 557	80
2	white 2	455 and 557	80
3	blue 1	417	80
4	blue 2	417	80
5	red	673	160
6	infrared	745	160

The illumination area of the chambers are 0.74 m × 0.41 m, so the plants in the cultivation pallets (0.60 m × 0.30 m) are completely covered. Figure 3 shows an example of the spatial distribution of the illumination, based on the maximum value in the respective chamber, as a surface diagram.

Repeated measurements and comparison of the results between the modules of the chambers reveal, that the PPFD deviates far from the nominal values. For this reason, the irradiance in the climate chambers and the radiant power in the

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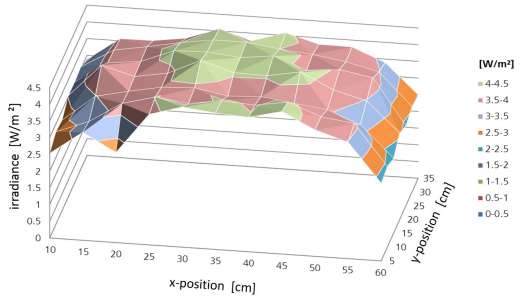

Figure 3: Spatial light distribution within a climate chamber (LED module type 1).

integrating sphere are measured over a period of several hours.

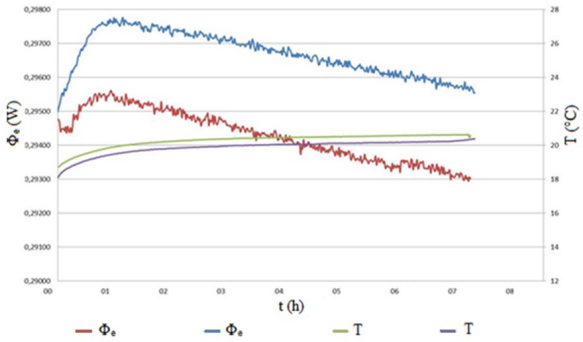

Figure 4: Illumination drop of LED module type 1.

Figure 4 shows the radiant power of the LED modules for two consecutive days with the associated ambient temperatures in the integrating sphere. A drop in the radiation power over the operating time can clearly be seen. The power curve for the second day (red) first rises to the last measured value on the first day (blue), but then drops further at the same rate. Further long-term measurements over a period of one month provide a PPFD reduction of 0.01 µmol/(ms^2) per hour.

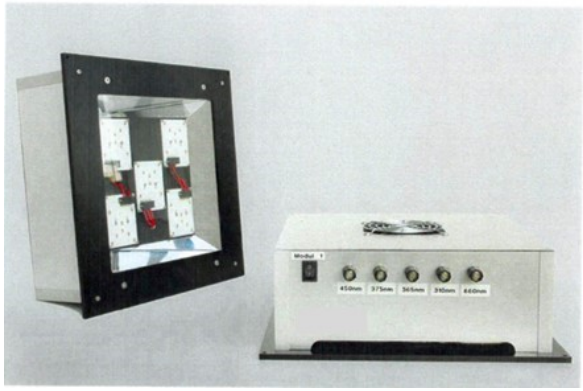

Figure 5: LED module UMSICHT (type 2).

Due to the degradation of Module 1, another module have been developed (see Figure 5).

LEDs with wavelengths of 310 nm, 365 nm, 375 nm, 450 nm and 660 nm have been used, which can be controlled individually.

The spatial distribution and the degradation of this modules (type 2) turned out to be much better compared to type 1 modules. Figure 6 shows the spatial distribution.

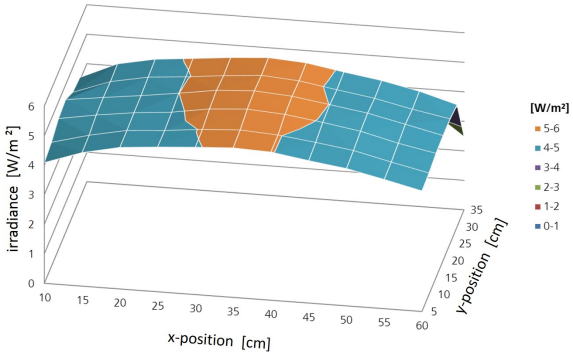

Figure 6: Spatial distribution LED module UMSICHT (type 2).

For the planned development of growth protocols, the experimental design is carried out using statistical methods (DOE, Design Expert).

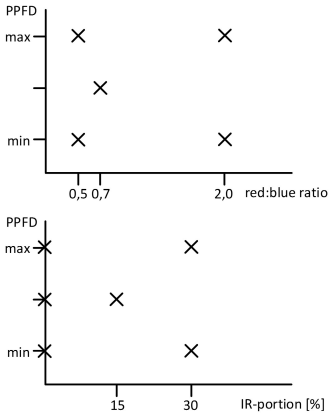

Figure 7: Experimental design.

For this purpose, a two-factor factorial design (linear dependencies) according to Figure 7 have been chosen. For each of the factors (red:blue ratio and IR portion) a separate design was determined, which is examined in separate chambers. The red:blue ratio for the IR-portion is 1 in each case.

Differing calibration methods of the optical measuring device led to the variations of the experimental design seen in Figure 7, the repetition tests are carried out under these conditions in order to ensure a comparability of the measurement results (planned: red:blue ratio

1, 190 µmol/(ms^2), actual red:blue ratio 0,7, 190 µmol/(ms^2)).

After the illumination phase the plants are harvested, extracted and the plant metabolisms (anthocyanins and flavonols) were analyzed by HPLC analysis.

The pre-cultivation of the plants (spinach, chard, lovage, buckwheat herbs and lambs lettuce) has been carried out for six weeks under SON-T lamps, as these lamps are often used in conventional plant applications. Unlike the LEDs, SON-T lamps emit the complete VIS-spectrum. In the end of the pre-cultivation phase, the plants are thinned out (only one plant per pot remains). The removed plants are analyzed by HPLC to serve as a reference for the following exposure phase.

Using the example of lovage, in the following the change of the absolute rutin concentration related to the reference (SON-T lamps) is considered. From Figure 7 it can be seen that different LED exposure scenarios can influence the rutin concentration positively or negatively.

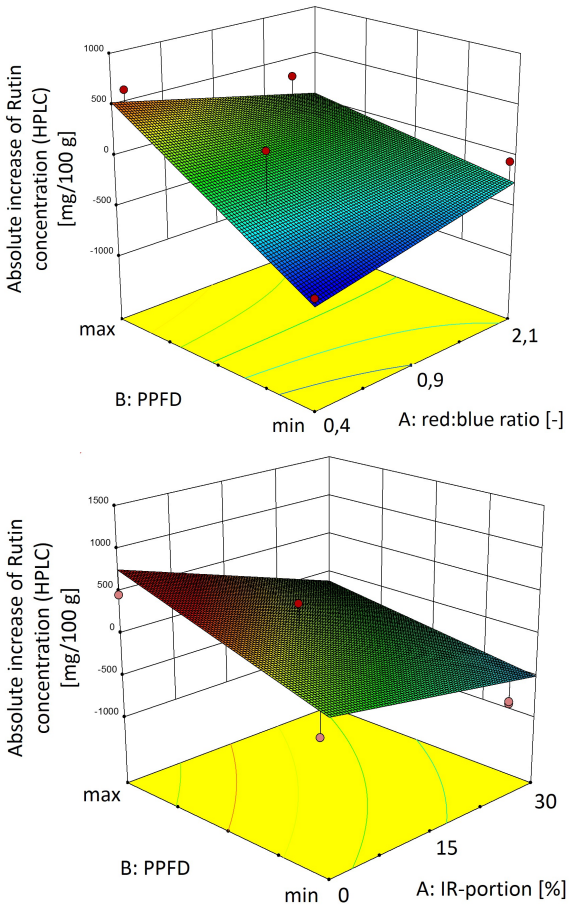

Figure 8: Absolute increase of rutin concentration (top: red:blue ratio; bottom: IR-portion).

For example, with a red:blue ratio of 0.4 and an irradiance of 80 µmol/(ms^2) the rutin concentration is lowered by about 600 mg/100 g, while it is increased by 620 mg/100 g at an irradiance of 300 µmol/(ms^2).

While the rutin concentration decreases with increasing IR portion (see Figure 8), the biomass increases in the experiments with an increasing IR-portion (ref. Figure 9).

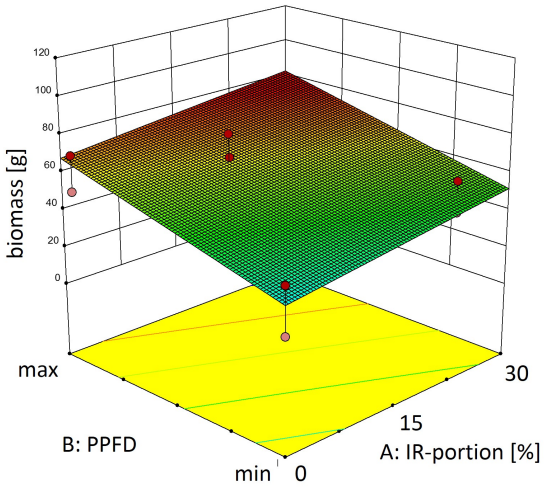

Figure 9: Biomass at different IR-portions.

Conclusions

Spinach, chard, lovage, buckwheat herbs and lambs lettuce were examined concerning the influence of light on the formation of anthocyanines and flavonols in the plants.

To realize homogeneous light in the climate chambers different LED-modules were tested. One module met the necessary requirements to emit the light evenly distributed without degradation over the whole testing period. Growth protocols were developed for the different plants using different light scenarios.

To summarize, the formation of anthocyanines and flavonols is definitely affected by light compositions, i. e. by varying the ratios of red:blue and adding IR. Concerning the LED-modules it is necessary to measure the illumination of each single module, including long-term tests to identify degradation. To examine all influencing factors, it is necessary to carry out further experiments considering different spectral compositions, intensities, and photoperiods.

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References

[1] Samanta, Amalesh; Das, Sanjoy Kumar; Das, Gouranga: Roles of flavonoids in plants. In: Int. Journal Pharm Sci Tech 2011 (6).

[2] Perez-Balibrea S, Moreno DA and Garcia-Viguera C, Influence of light on health-promoting phytochemicals of broccoli sprouts. JSciFood Agric 88:904–910 (2008).

[3] Mou B, Nutrient content of lettuce and its improvement. Curr Nutr Food Sci 5:242–248 (2009).

[4] Tiwari B, Brunton NP and Brennan CS, Plant food phytochemicals. in Handbook of Plant Food Phytochemicals: Sources, Stability and Extraction, ed.by Tiwari BK, Brunton NP and Brennan CS. John Wiley & Sons Ltd, Oxford, PP. 1–4 (2013).

[5] Walters RG, Towards an understanding of photosynthetic acclimation. JExp Bot 56:435–447 (2005).

[6] Bian ZH, Yang QC, Liu, WK: Effects of light quality on the accumulation of phytochemicals in vegetables produced in controlled environments: a review. J Sci Food Agric 2015, 95: 869–877 (2014)

[7] Dlugosz-Grochowska, Olga; Wojciechowska, Renata; Kruczek, Michal; Habela, Anna (2017): Supplemental lighting with LEDs improves the biochemical composition of two Valerianella locusta (L.) cultivars. In: Hortic. Environ. Biotechnol. 58 (5), S. 441–449. DOI: 10.1007/s13580-017-0300-4.

[8] Lobiuc, Andrei; Vasilache, Viorica; Pintilie, Olga; Stoleru, Toma; Burducea, Marian; Oroian, Mircea; Zamfirache, Maria-Magdalena (2017): Blue and Red LED Illumination Improves Growth and Bioactive Compounds Contents in Acyanic and Cyanic Ocimum basilicum L. Microgreens. In: Molecules (Basel, Switzerland) 22 (12). DOI: 10.3390/molecules22122111.

[9] Garcias-Marcias P, Ordidge M, Vysini E, Waroonphan S; Changes in the flavonoid and phenolic acid contents and antioxidant activity of red leaf lettuce (Lollo Rosso) due to cultivation under plastic films varying in ultraviolet transparency, J Agric Food Chem, 2007.

[10] Kim, Yong Hyeon; Lee, Jae Su (2016): Growth and Contents of Anthocyanins and Ascorbic Acid in Lettuce as Affected by Supplemental UV-A LED Irradiation with Different Light Quality and hotoperiod. In: Korean J. Hortic. Sci. Technol. 34 (4). DOI: 10.12972/kjhst.20160061.

[11] Li Q and Kubota C, Effects of supplemental light quality on growth and phytochemicals of baby leaf lettuce. Environ Exp Bot 67:59–64 (2009).

[12] Goto, E., et al. Effect of UV light on phytochemical accumulation an expression of anthocyanin biosynthesis in leaf lettuce. Acta Hortic 1134.

[13] Yanovsky MJ, Alconada-Magliano TM, Mazzella MA, Gatz C, Thomas B and Casal JJ, Phytochrome A affects stem growth, anthocyanin synthesis, sucrose-phosphate-synthase activity and neighbour detection in sunlight-grown potato. Planta 205:235–241 (1998).

[14] Mizuno T, Amaki W and Watanabe H, Effects of monochromatic light irradiation by LED on the growth and anthocyanin contents in leaves of cabbage seedlings, in VI International Symposium on Light in Horticulture 907, ed. by Goto E, Hikosaka S. ISHS, Belgium, pp. 179–184 (2009).

[15] Samuoliene G, Sirtautas R, Brazaityte A and Duchovskis P, LED lighting and seasonality effects antioxidant properties of baby leaf lettuce. Food Chem 134:1494–1499 (2012).

[16] Samuoliene G, Viršile A, Brazaityte A, Jankauskiene J, Duchovskis P, Novickovas A, et al, Effect of supplementary pre-harvest LED lighting on the antioxidant and nutritional properties of green vegetables, in XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 939, ed. by Desjardins Y. ISHS, Belgium, pp. 85–91 (2010).

Closed Loop Control Systems for Supplementary Lighting in Smart Greenhouses

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Abstract

With the global trend of increasing urban population, there is therefore an observably growing demand for fresh, high quality, flavor and nutrition-rich food to be supplied for the consumers. The main market drivers of LED based Greenhouse, Hydroponic and Aeroponic food production are increasing production- and labor costs, challenging weather- and climatic conditions and increasing electricity prices; combined with the higher achievable profit by consistent production and premium quality products.

While pure natural lighting is considered to be the most energy efficient for growing plants, for the increased yield, continuous production and forecast-able yield, it is often financially beneficial to apply supplementary lighting; especially during seasons with lower Daily Light Integral (DLI). Then the goods sell prices are higher and in some instances, the production was to be suppressed for this time frame due to inappropriate light conditions.

This paper focuses on the estimation of DLI per-region as well as per-season in the EMEA region, the lighting requirements of a certain plant and introduces a method for calculating the peak Return on Investment (RoI) therefore of artificial lighting systems. The aim is to compare fixed Photosynthetic Photon Flux (PPF) systems with adaptive spectral- and intensity controlled solutions from a Total Cost of Ownership (TCO) point of view and briefly introduce core technologies available for the latter technical approach.

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Introduction

Systems, where the quantitative output has no effect on the input to the control process are called open-loop control systems. In the lighting practice, this covers those installations, where the luminaires are either not dimmable at all, or are being dimmed according to a preset scheme that is pre-programmed. This covers over 99% of all the artificial lighting installed in the agriculture landscape [1]. Closed loop control systems on the other hand utilize sensory data as a feedback for a basis of actuation correction and thus reducing the error between the controlled variable and the reference value. While Carbon Dioxide (CO_2), Plant Nutrition and Temperature Control systems are well established in the grower market, precise light measurement and tuning is a long standing technical challenge.

The basis for the need of these advanced irradiation capabilities roots in the nature of plants. All-around from the different species down to the minor alternations of sub-breeds; varied with the current life-cycle, growth phase and stage, plants have different lighting needs for Photosynthesis, healthy rooting, biomass increase and even for protection against infections or pesticides. Both undergoing a certain threshold and surpassing an upper limit can lead to reduced yield [2], lower quality and even to the forfeiture of an entire harvest [3] in extreme cases.

Lighting requirements

For the proper development of any given plant, there are two metrics of irradiation to be controlled. Photosynthetic Photon Flux Density (PPFD), measured in [uMol/m^2/s] is the number of photons of the Photosynthetic Active Radiation (PAR) reaching a given surface unity.The PAR is a slice of the electromagnetic radiation that is considered to be the useful region of the visible light spectrum for stimulation of photosynthesis, meaning that any photons within this spectrum that are absorbed by the plant might contribute to photosynthesis. PPFD is the timid differential of this energy, yielding the flux to a surface area.

While too low PPFD is generally not an issue — as plants have always experienced this during their evolutionary life-cycle within nighttimes, over-lighting (the term generally used for providing an extreme amount of lighting for a brief period of time) leads to tissue damage, mostly observable as leaf yellowness and tip-burn [2].

The other approach for the control of growth is the integration of the PPFD on a reasonable time frame. This is known as the Daily Light Integral (DLI), measured in [Mol/m^2 day], that describes the number of photo-synthetically active photons that are delivered to a specific area over a 24-hour period.

The DLI has a significant impact on a number of plant variables, including rooting, stem thickness, plant height, branching and flowering. Figure 1 shows the effect of different average cultivation DLI levels on yield for butterhead lettuce [4]. It can be seen that with higher Daily Light Integral, the Shoot Dry Mass was higher, as described in Both et als experiments.

Figure 2 describes a linear correlation between DLI and yield on the range of about 300 mol/m^2 to 820 mol/m^2 which means with high confidence that for this specific breed, under similar circumstances, the following equation describes the total Shoot Dry Mass:

$$DM = -1.886 + \alpha \quad (1)$$

$$R^2 = 0.87 \quad (2)$$

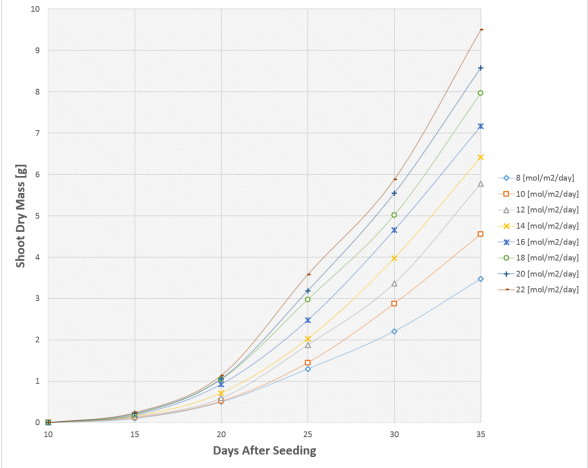

Figure 1: Fitted growth curves for butterhead lettuce (cultivar Ostinata) based on the daily integrated light level maintained during the production cycle (35 days).

This linear fitted curve might induce that more light will always increase production for butterhead lettuce. Obviously though, production can not be increased infinitely in a given surface area.

Even with fine tuned environmental conditions, the excess PAR lighting reaches a saturation in

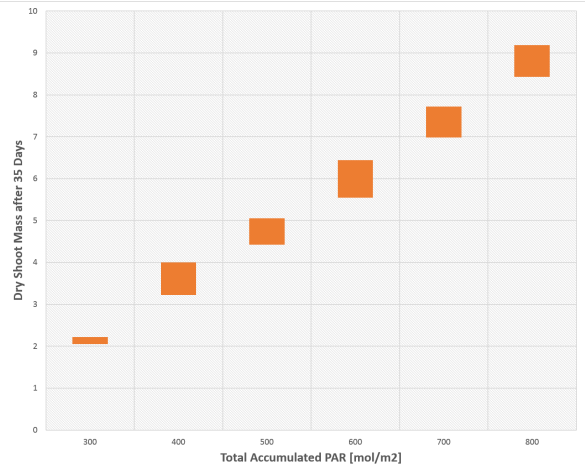

Figure 2: Shoot Dry Mass as a function of Total Accumulated Light levels (since seeding).

Photosynthesis. The butterhead lettuce example to be continued, Daily Light Requirement can be divided into four morphological phases of development, as shown in [5].

For a practical explanation of the effect of DLI on yield, Figure 3 shows the average daily PPFD of a specific region and the corresponding Tomato shipments.

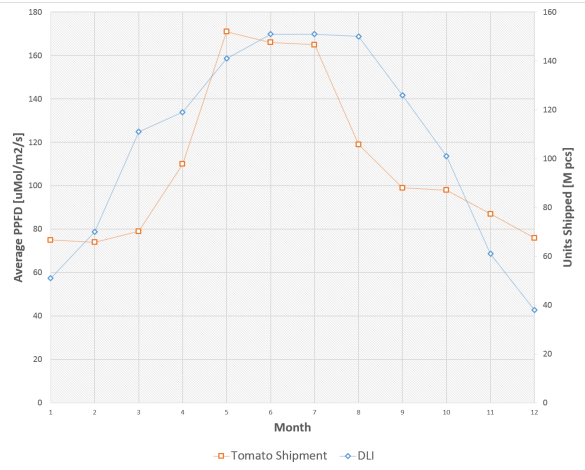

Figure 3: Regional Tomato shipment and average solar PPFD.

Seedlings

During the seeding phase, about 50 uMol/m^2/s irradiance in a 24 hr/day photoperiodism is usual in Hydroponic greenhouse production, as introduced in [5]. This results a DLI of about 5 Mol/day. Seedlings can be successfully cultivated under either low-level natural light or even artificial light only. Very shortly after the seedlings are germinated, and even before the first true leaf is visible, the plant starts responding to environmental light levels. If the seedling is not getting enough light, the cells in the plant stem will elongate, pushing the cotyledons and the first leaf upwards, to seek more light. As a result, a thin-stemmed, weak plant is produced. If the plant survives, the stem will never thicken to equal the normal size at the base of the plant [6]. However, if there is enough light for the young seedlings while the first true leaf is developing and is about to expand, the base of the stem will remain compact and the cotyledons will not rise to an excessive height. Seedlings are typically germinated on 10 “by 20” or similar sized trays (seedbeds) per 200 pcs of seedlings — or in similar densities — in production environments. In order to provide optimized cultivation conditions, the plants are to be morphologically controlled by artificial lighting in this first phase of the generative cycle for optimum yield and plant quality.

Nursery operations

Continuing the planting, from the first day after seedling to about the 10th day, a minimum of 200 uMol/m^2/s to an average of 250 uMol/m^2/s is to be provided, again, in a 24 hr/day photoperiodism. The DLI can reasonably be pushed all the way up to 30 Mol/day or even higher for some breeds. This 30 Mol/day setup means a continuous 350 uMol/m^2/s irradiance throughout the entire day. This is only possible with the application of artificial lighting. Controlling both the minimum and the maximum of the irradiance are both important for proper generative phase. In practice, usually, the same seedbeds are being used before the first re-potting after the 10th day. Hence, the density is still about 1000 plants per m^2. Over-lighting the plants prohibits a race amongst the plants and one will develop to the harm of an other; while plants will distort due to rapid development that is not beneficial for further growth phases and overall yield. Excess over-lighting also causes leaf damage [7].

First re-potting and Phytochrome photoperiodism

As the seedbeds are physically saturated, there is a need to re-pot the plants. This usually happens in 2 phases for space utilization. In the first stage, density is decreased to about 80 plants per m^2.

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This gives more space to grow independently, while also enables proper light utilization. This is often referred to as lighting task efficiency. Photoperiodism decreases to 20 hr/day. There are several papers to claim that a 'resting period' is necessary at this stage of growth. DLI is between 15 to 17 Mol/day. With the period introduced, there is an additional term to be considered for the transition of day and night cycles.

Phytochrome is a plant pigment protein that absorbs red light and then initiates physiological responses governing light sensitive processes such as germination, growth and flowering. This exists in two forms, pr and pfr, that are inter-converted by light. A plant pigment that exists between two forms, phytochrome 660 and phytochrome 725. They switch between one or the other depending on what time of the day it is, daytime or night time [8]. The practical application of this is the simulation of nighttime transition with Photo Red and Far Red LEDs selective dimming. This function can lead to increased yield with many plant types [9].

Second re-potting

The second re-potting happens for the same reason as the first, on about day 20 from seedling. Economically, it is not beneficial in the EMEA region to further tear down the utilization with finer steps, as this process also has substantial resource requirements. DLI should be kept around 15 to 17 Mol/day with the same 20 hr/day photoperiodism. Using (or abusing) Phytochrome reactions is also beneficial hereby [9].

General rules

As shown, both a minimum and a maximum of both the irradiance and the DLI can be defined for the different growth stages for leafy greens. The definition of the values shall be based on growing efficacy; considering the resource requirement of a given setup compared to the yield and the product quality. Figure 4 shows the light response curve of Photosynthesis for A. longicaulis, a typical shade-tolerant plant [9]. This is a great example of a saturation point. Up until a certain level, more light results higher Net Photosynthetic Rate in a linear correlation and thus higher net yield.

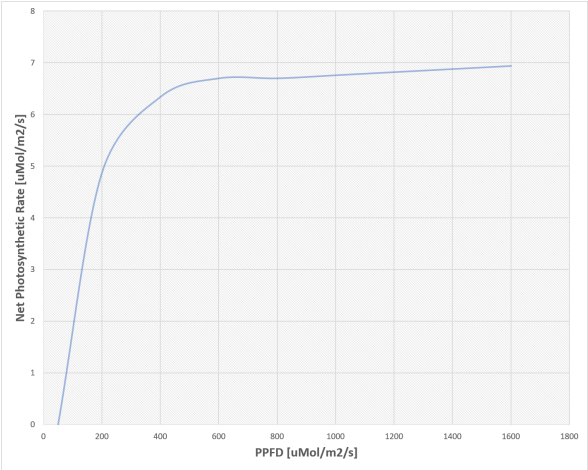

Figure 4: Light response curves of net assimilation rate for A. longicaulis plants.

Natural DLI in greenhouses

As in every single functional artificial lighting scenario, energy consumption and Return on Investment is a key factor when considering the installation of a set of luminaries. The key goal of greenhouse supplementary lighting is to provide sufficient PPFD for a growing task. This can be covered either fully from natural daylight or with the help of light sources. When there is plenty of natural sunlight, as shown in the previous section, it is not always rational to turn on this extra source of PPF as the excess electrical consumption will not be paid off of the additional yield achieved.

Figure 5 shows the DLI requirement for butterhead lettuce (generative) and the Average Natural DLI Availability in a specific European greenhouse. It is very important for a reliable lighting design to consider geographic location based natural PPFD for a Year span. This is a key enabler for an accurately planned cost analysis of a lighting project; in order to estimate Yield increase, productivity time-frame enhancement and Total Cost of Ownership (TCO).

Figure 5 highlights the region specific DLI throughout the Year. This however, is not equal at all with the DLI inside the construction. For some part of the Year, there is only a loss on the semi-transparent, slightly diffuse walls. From Calendar Week (CW) 14 though, there is a whitewash applied to the shell of the building. The main purpose is to reflect unnecessary light and heat during the months with extreme natural irradiation. This normally wears off around CW 35 to 40, when the average solar radiation falls below the critical level for cultivation.

Figure 5: DLI requirement for butterhead lettuce (generative) and Average natural DLI availability in an European greenhouse.

Figure 6 indicates the same overhead analysis for seedlings. In this case, neither the additional heat, nor the additional daylight are to be limited and thus, no whitewash is applied. In this era, the recommended DLI was designed for 21.6 Mol/day and the minimum to 17.3 Mol/day in this specific case. Photoperiod was set to 24 hr/day. This setup is capable of a production of 110 plants per m^2 per day.

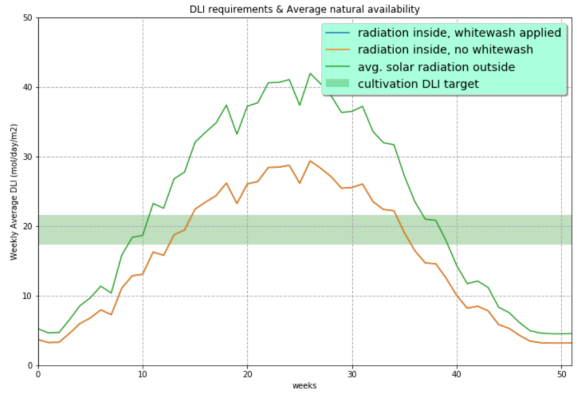

Figure 6: DLI requirement for butterhead lettuce (seedling) and Average natural DLI availability in an European greenhouse.

In this case, for this region, the supplementary lighting has to provide 174 uMol/m^2/s at its peak power for reaching the minimum production PPFD target statistically in at least 70% of the days with 95% confidence. Figure 7 shows us the necessary supplementary lighting level throughout the Year, aiming for a solution, where the minimum DLI is reached at maximum power and this PPF is used as long as it will cover the maximum of the cultivation DLI target. After that level, the value fills only the gap to the maximum and never more.

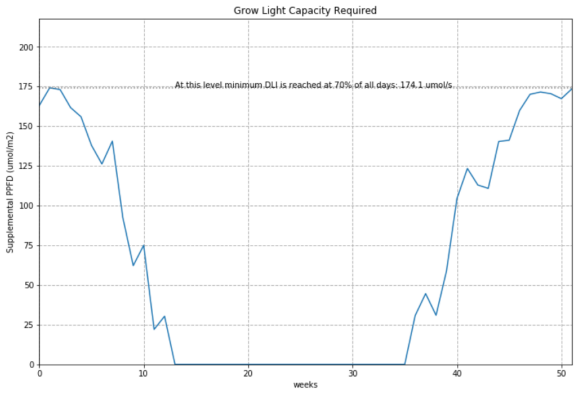

Figure 7: PPDF Grow light capacity requirement for meeting growth targets.

Growing strategy

As shown, the rationality of artificial lighting is always dependent of several key factors. The main points for TCO analysis to be considered are:

- Natural Solar DLI in the Greenhouse
- Cultivation DLI target
- Sales price of the product
- Sales price of the product when Natural Solar DLI does not cover the cultivation DLI requirements
- Electricity cost
- Cost of the lighting installation
- Maintenance costs

While lower maintenance cost and savings on electricity are obvious aspects of profit, quantifying the additional revenue on the extra sales when the product can be sold at a higher price is not always easily forecast-able. Figure 8 shows the correlation of average sales price with natural DLI for Tomato in a South European territory. This is very much plant dependent, and can be a good indication of the profitability of a supplementary lighting investment.

Continuing the example with butterhead lettuce, Figure 9 shows the dimming levels of an intelligent growing system, where the PPF of the fixtures is controlled in order to meet the cultivation target as introduced before.

In this setup, the luminaires have 4096 hr annual ontime of which in 1018 hr are operating at full power and for the remaining time are dimmed to a desired level. Figure 10 shows the operational time accumulation over a Year for such a fixture (left) and the additional PAR photons compared to the Solar PAR.

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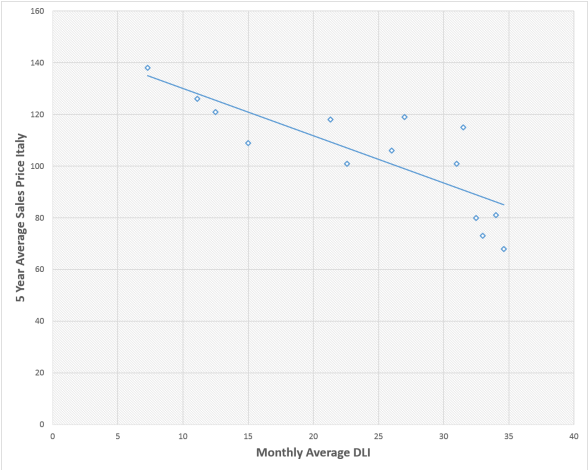

Figure 8: Average sales price to Solar DLI.

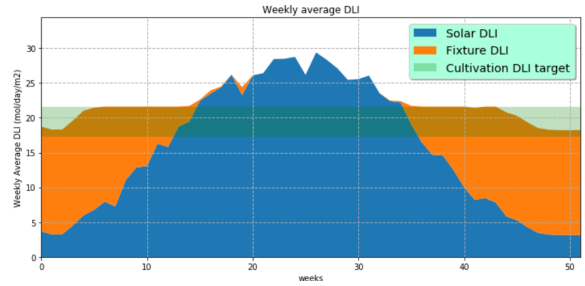

Figure 9: Supplementary PPFD with intelligent Greenhouse lighting.

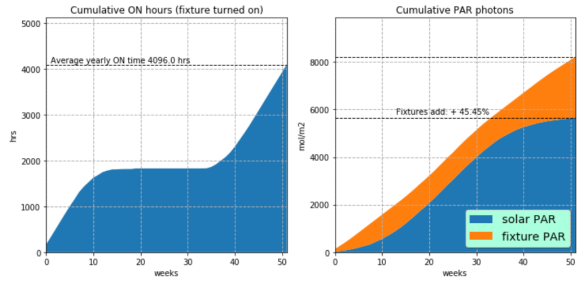

Figure 10: Supplementary light accumulation and PAR Photon comparison.

Production analysis

Another way to instantiate the Yield increase is plotting the production time through each CW of the Year; with and without artificial lighting and comparing results considering electricity costs for each period. In some cases, it is worthy to go for the saturation point of irradiance, in some cases it will not cover the cost of the photon production. Figure 11 shows the unit production time of a lettuce production facility per plant on average. Optimal cycle is 25 days from seeding, with respect to processing and quality. In this specific case, revenue was maximized by letting the production time per unit to be increased to 32 days during darker periods of the Year. This also includes reduced workforce labor costs.

Figure 12 introduces the extra expected yield per growing area for this case study.

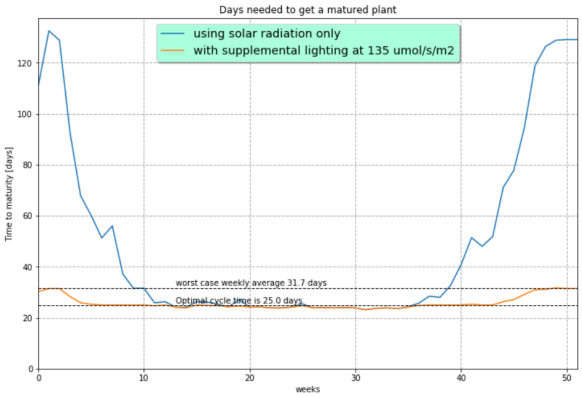

Figure 11: Supplementary light accumulation and PAR Photon comparison.

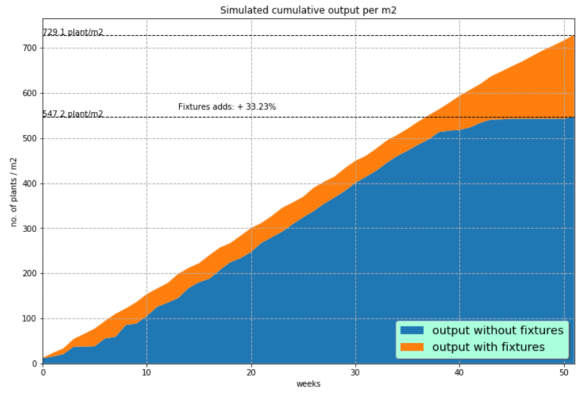

Figure 12: Supplementary light accumulation and PAR Photon comparison.

Conclusions

There was a trend for long in Agriculture of establishing automatic systems that have been doing repetitive processes with less and less involvement of human operators. The next step of such infrastructures will be smart systems with programed decision making algorithms maximizing profit for growers. This inevitably leads to artificial intelligences controlling artificial lighting, planting, watering, gas controlling systems for modern food production.

As for the current state of the art; it is possible to accurately measure PPFD and spectral distribution of the incoming light at task planes that opens the way to event driven, closed loop light control in machine-supervised growing environments.

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It was shown that these systems have several increased benefits over conventional systems, including maximizing RoI and Production while optimizing costs and controlling quality.

References

[1] marketsandmarkets.com, Grow Light Market by Technology (HID, Fluorescent, LED, Induction, and Plasma), Type of Installation (New and Retrofit), Application (Indoor Farming, Commercial Greenhouse, Vertical Farming, Research), and Geography — Global Forecast to 2022, March, 2017, SE 4140

[2] A. Brazaitytė, A. Vir¿ilė, G. Samuolienė, J. Jankauskienė, S. Sakalauskienė, R. Sirtautas, A. Novičkovas, L. Daba¿inskas, V. Va¿takaitė, J. Miliauskienė, P. Duchovskis, Light quality: growth and nutritional value of microgreens under indoor and greenhouse conditions. 10.17660/ActaHortic.2016.1134.37, ISHS Acta Horticulturae 1134: VIII International Symposium on Light in Horticulture

[3] Andrea J. Buonassisi, M.Sc, P. Ag, Consulting Plant Pathologist 1762 Taralawn Court, Burnaby, BC, V5B 3H5, Biosecurity Guidelines for Post-harvest Greenhouse Tomatoes: Prevention of Post-harvest and Storage Rot. B.C. Ministry of Agriculture.

[4] A.J. Both, TEN YEARS OF HYDROPONIC LETTUCE RESEARCH, Rutgers, The State University of New Jersey.

[5] Dr. Melissa Brechner, Dr. A.J. Both, CEA Staff, Hydroponic Lettuce Handbook, Cornell Controlled Environment Agriculture, `http://www.cornellcea.com/attachments/CornellCEALettuceHandbook.pdf`, referenced: 2018.05.04

[6] James W. Brown, Light in the Greenhouse: How Much is Enough?, `https://www.hort.vt.edu/ghvegetables/documents/GH_Lighting/Light_in_the_Greenhouse_JBrown.pdf`, referenced: 2018.05.04.

[7] Marina I. Sysoeva, Eugenia F. Markovskaya, Tatjana G. Shibaeva, Plants Under Continous Light: A Review, Institute of Biology, Karelian Research Centre, Planr Stress, Global Science Books, 2010

[8] Daedre S. Craig, Erik S. Runkle, A Moderate to High Red to Far-red Light Ratio from Light-emitting Diodes Controls Flowering of Short-day Plants, JASHS May 2013 vol. 138 no. 3 167–172

[9] Qiansheng Li, Min Deng, Yanshi Xiong, Allen Coombes, Wei Zhao, Morphological and Photosynthetic Response to High and Low Irradiance of Aeschynanthus longicaulis, ScientificWorldJournal. 2014; 2014: 347461. Published online 2014 Jun 30. doi: 10.1155/2014/347461

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Universal LED Tubes: Detailed Descriptions of Design, Technologies and Market

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Abstract

Linear fluorescent, with approximately 12 billion tubes installed worldwide, is the biggest segment in the lighting industry that still largely has to make the transition to LED.

Only recently attractive *retrofit* solutions became available that combine high luminous efficacy (energy savings) with full, nearly 100%, backwards compatibility on all ballasts in the field (easy to install). The near perfect compatibility is obtained by continuing to use the ballast, originally present to supply stable power to the fluorescent tube, as the power supply for the LED tube whilst keeping the ballast in its intended mode of operation. This is achieved by configuring the LED's and other passive components (inductors, capacitors) depending on the type of ballast sensed by the on-board driver of the LED tube.

This paper describes this development, its expected immediate impact on a market with regulators that want to get rid of mercury containing lamps[1] and (near) future developments.

[1] Karl-Heinz Florenz, question to the commission of the EU, March 12 2018

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Introduction

The LED industry has been successful in providing retrofit solutions for most incumbent light sources. This has led to a rapid ledification of many lighting segments and thus contributed to very significant energy savings around the globe. One of the remaining challenges is to retrofit fluorescent tubes, which, once achieved, will bring, besides energy savings, a very important contribution to the eradication of mercury from the environment, one of the goals of the RoHS regulation. The origin of this challenge is the huge number of different ballasts installed in the field to operate fluorescent tubes. This not only leads to differences between retrofit projects, but even more challenging is the fact that as a result of regular maintenance over the years there can be substantial differences between the ballasts found within one and the same retrofit project, further reducing the chance of successful retrofitting when the tubes ballast-compatibility is not near 100%. Over the last 5 years we have developed and brought to the EU market a cost effective universal solution with unsurpassed ballast compatibility, which offers to installers the user friendly universal retrofit solution they are looking for. The heart of this solution is to use the ballast, be it magnetic or electronic, as the supply of energy to the LED's and to configure LED's and LED tube electronics accordingly. We complement this with a robust, purely mechanical solution to address the safety requirements for a universal tube. In this presentation we will describe the electronics and mechanical aspects of this solution in detail and show its validation on a large variety of different ballasts. Next general market developments and the go to market strategy which we implemented with our partners is described. Learnings in the market will be shared. Finally extensions of the working principle to address market needs such as direct mains and reduced power spread are briefly discussed.

Working principle

Ballasts in countries with 230 V mains voltage, come in three varieties:

- an inductor in series with the tube (called magnetic ballast (MB) or conventional control gear, CCG)
- an electronic circuit which is either a switched mode power supply of constant current type switching in the range of 25 to 65 kHz or
- a self-resonant electronic circuit of constant power type with a typical resonance frequency in the range of 25 to 40 kHz (electronic control gear, ECG).

There is a few orders of magnitude difference between the AC frequency of the output of magnetic ballasts compared to electronic ballasts, which we use to detect the difference between one and the other and then configure the LED's optimally.

In case of electronic ballast, the optimum LED Vf, which acts as voltage clamp, is set by the target power of the lamp and the preferred operating window of the ballast. Typical value we apply in practice is between 50 and 60 V. Connecting a (multiple of parallel) 60 V LED string(s) to a magnetic ballast, however, would lead to a very high power (up to 100 W) of the tube ballast combination, which moreover is not regulated, meaning that relatively small variations in the mains voltage will lead to very significant changes in the LED current and the resulting light output. This leads to visible erratic light flux intensity variations (flicker) and unacceptably poor line regulation.

The solution to this is displayed in Figure 1 and consists of two key ingredients. First is to rearrange, when on a magnetic ballast, the parallel strings of LED's into one series string of LED's, with a Vf close to 300 V. The resulting power, when put on a standard 58 W ballast is an LED power of roughly 12 W which then is boosted to 25 W with a boosting circuit switching at twice the line frequency and using the same magnetic ballast as its inductor, which is the second key element of the solution.

During the on time of the boosting, which is during the initial phase of the mains sine-wave, a part of the series configuration of LED's is bypassed, which results in a lower Vf for the duration of which the ballast can and will deliver a much higher current. Finally, measuring and controlling the total current results in a well regulated system.

Validation

Critical to success of a universal solution is that it functions well on each ballast installed in the field. There are many hundreds of different ballasts and

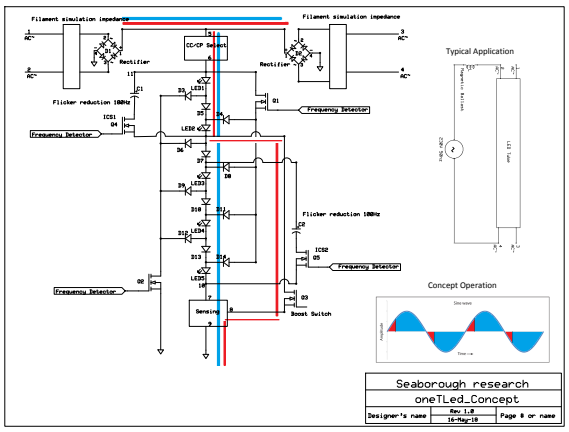
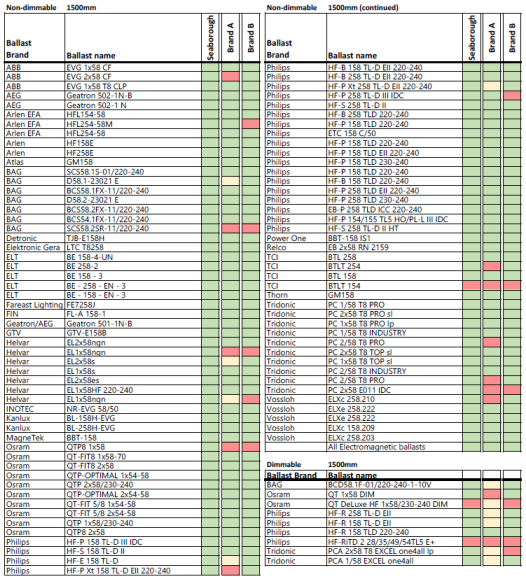


Figure 1: The solution for a universal tube: multiple LED strings with the correct clamp voltage for the target power on electronic constant current ballasts, which are put in parallel on electronic ballasts by charge-pump driven switches that use the frequency information from the input signal to become triggered (or not), are kept in series on a magnetic ballast. Once configured, in case of magnetic ballast, the clamp voltage of the LED load is switched to a reduced value in the early phase of the sinusoidal output voltage of the ballast which results in higher current (red color). The use of current sensing to regulate the duty cycle between the two load configurations results in very precise power and line regulation.
Finally, when the current exceeds a certain threshold, the ballast is identified to be of constant power type and an extra inductor is switched in series with the LED load which results in a significant reduction of ballast current without losses and thus to reduced overall system power.



Non-dimmable	1500mm			
Ballast Brand	Ballast name	Seaborough	Brand A	Brand B
ABB	EVG 1x58 CF			
ABB	EVG 2x58 CF			
ABB	EVG 1x58 T8 CLP			
AEG	Geatron 502-1N-B			
AEG	Geatron 502-1 N			
Arlen EFA	HFL154-58			
Arlen EFA	HFL254-58M			
Arlen EFA	HFL254-58			
Arlen	HF158E			
Arlen	HF258E			
Atlas	GM158			
BAG	SCS58.1S-01/220-240			
BAG	DS8.1-23021 E			
BAG	BCS58.1FX-11/220-240			
BAG	DS8.2-23021 E			
BAG	BCS58.2FX-11/220-240			
BAG	BCS54.1FX-11/220-240			
BAG	SCS58.2SR-11/220-240			
Detronic	TJB-E158H			
Elektronic Gera	LTC TB258			
ELT	BE 158-4 UN			
ELT	BE 258-2			
ELT	BE 158 - 3			
ELT	BE - 258 - EN - 3			
ELT	BE - 158 - EN - 3			
Fareast Lighting	FE7258J			
FIN	FL-A 158-1			
Geatron/AEG	Geatron 501-1N-B			
GTV	GTV-E158B			
Helvar	EL2x58ngn			
Helvar	EL1x58ngn			
Helvar	EL2x58s			
Helvar	EL1x58s			
Helvar	EL2x58es			
Helvar	EL1x58HF 220-240			
Helvar	EL1x58ngn			
INOTEC	NR-EVG 58/50			
Kanlux	BL-158H-EVG			
Kanlux	BL-258H-EVG			
MagneTek	BBT-158			
Osram	QTP8 1x58			
Osram	QT-FIT8 1x58-70			
Osram	QT-FIT8 2x58			
Osram	QTP-OPTIMAL 1x54-58			
Osram	QTP 2x58/230-240			
Osram	QTP-OPTIMAL 2x54-58			
Osram	QT-FIT 5/8 1x54-58			
Osram	QT-FIT 5/8 2x54-58			
Osram	QTP 1x58/230-240			
Osram	QTP8 2x58			
Philips	HF-P 158 TL-D III IDC			
Philips	HF-S 158 TL-D II			
Philips	HF-E 158 TL-D			
Philips	HF-P Xt 158 TL-D EII 220-240			

Non-dimmable	1500mm (continued)			
Ballast Brand	Ballast name	Seaborough	Brand A	Brand B
Philips	HF-B 158 TL-D EII 220-240			
Philips	HF-B 258 TL-D EII 220-240			
Philips	HF-P Xt 258 TL-D EII 220-240			
Philips	HF-P 258 TL-D III IDC			
Philips	HF-S 258 TL-D II			
Philips	HF-B 258 TLD 220-240			
Philips	HF-P 158 TLD 220-240			
Philips	ETC 158 C/50			
Philips	HF-P 158 TLD 220-240			
Philips	HF-P 158 TLD EII 220-240			
Philips	HF-P 158 TLD 230-240			
Philips	HF-P 158 TLD 220-240			
Philips	HF-B 158 TLD 220-240			
Philips	HF-P 258 TLD EII 220-240			
Philips	HF-P 258 TLD 230-240			
Philips	EB-P 258 TLD ICC 220-240			
Philips	HF-P 154/155 TL5 HO/PL-L III IDC			
Philips	HF-S 258 TL-D II HT			
Power One	BBT-158 IS1			
Relco	EB 2x58 RN 2159			
TCI	BTL 258			
TCI	BTLT 254			
TCI	BTL 158			
TCI	BTLT 154			
Thorn	GM158			
Tridonic	PC 1/58 T8 PRO			
Tridonic	PC 2x58 T8 PRO sl			
Tridonic	PC 1x58 T8 PRO lp			
Tridonic	PC 1/58 T8 INDUSTRY			
Tridonic	PC 2/58 T8 PRO			
Tridonic	PC 2x58 T8 TOP sl			
Tridonic	PC 1x58 T8 TOP sl			
Tridonic	PC 2/58 T8 INDUSTRY			
Tridonic	PC 2/58 T8 PRO			
Tridonic	PC 2x58.E011 IDC			
Vossloh	ELXc 258.210			
Vossloh	ELXe 258.222			
Vossloh	ELXe 258.222			
Vossloh	ELXc 158.209			
Vossloh	ELXc 258.203			
	All Electromagnetic ballasts			

Dimmable	1500mm			
Ballast Brand	Ballast name			
BAG	BCD58.1F-01/220-240-1-10V			
Osram	QT 1x58 DIM			
Osram	QT DeLuxe HF 1x58/230-240 DIM			
Philips	HF-R 258 TL-D EII			
Philips	HF-R 158 TL-D EII			
Philips	HF-R 158 TLD 220-240			
Philips	HF-R/TD 2 28/35/49/54TL5 E+			
Tridonic	PCA 2x58 T8 EXCEL one4all lp			
Tridonic	PCA 1/58 EXCEL one4all			

Figure 2: The validation of the oneTLed solution for a universal 1500 mm tube and the comparison with other leading brands. In this overview compatible tube-ballast combinations are marked green, which means the end-user will not experience any adverse effects and both lamp and ballast will live up to their life time specification (temperature of components stays well within specification in relation to the rated life time of the tube and ballast). The color yellow marks tube-ballast combinations that show very noticeable variability in their stability and behaviour between different samples. Red marks combinations that do not function at all or components of the tube and/or ballast operate at temperatures well above their specification in relation to the rated life time.

we validate proper operation on as many as possible. Recent types can simply be bought and older types are obtained via demolition companies. For an example, see figure 2.

Special care needs to be taken to measure LED currents and ballast output powers at high frequencies to obtain reliable efficacy data.

Various additional aspects play a role in the definition of “compatibility”, besides the straightforward “does turn on and shows no flicker or erratic behaviour”. For example temperature of both ballast and lamp should remain within component specification for reliable operation.

In addition, for applications where actual realized power savings need to reach a minimum value guaranteed, the typical and maximum system power needs to be taken into account. In figure 3 we show the typical system and lamp power at equivalent usable luminous flux in a typical luminaire for the universal oneTLed in comparison with traditional fluorescent. Typical power savings of 40% are obtained for full distribution main stream mid power LED’s (cost effective).

To conclude a few remarks on the solution for countries with 120 V. The category of magnetic ballasts is substantially more diverse in that case, since it often is a transformer in its own right (to reach the required lamp ignition voltage) with a large variation in the secondary side voltage. The approach described in this paragraph is tested to be less suited for this situation. For this market the solution that includes AC mains, which we briefly address at the end of this paper, is the preferred one.

Safety endcap

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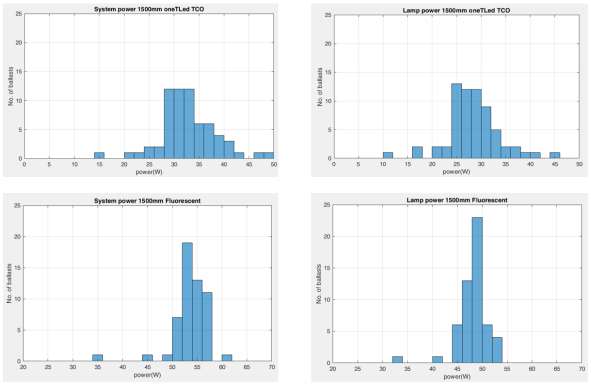

Figure 3: A histogram of the distribution of lamp and system power on electronic ballasts for the universal oneTLed solution (upper two panels) in comparison with traditional fluorescent tubes at equivalent usable light flux resulting from a "typical" luminaire. Power savings on average of more than 40% are realized with the use of full distribution main stream LED's.

General considerations

The IEC norms require that no risk of touch current exists when the tube is inserted in the luminaire. Two strategies can be found in the market to meet this requirement. The first is based on using mechnical switches on both ends which can only be activated once insertion of the tube is fully completed. Accidental switch-on should not be possible. The second strategy is to use relay switches inside the tube. Since there are a significant number of ballasts where the second strategy does not eliminate the touch current sufficiently well [1], we advocate the mechanical switch solution. A recall in June 2018 of universal tubes by a leading brand because of hazards of electric shock and electrocution further underlines the attractiveness of a mechanical switch solution.

Robust mechanical solution

When developing a mechanical switch solution, the following risks need to be eliminated respectively minimized:

- arcing, in the event of poor contact
- axial force (in the length direction of the tube) which pushes the lamp holder outwards which may result in loose and eventually loss of contact.

In figure 4 we show the mechanical solution thata addresses both these points.

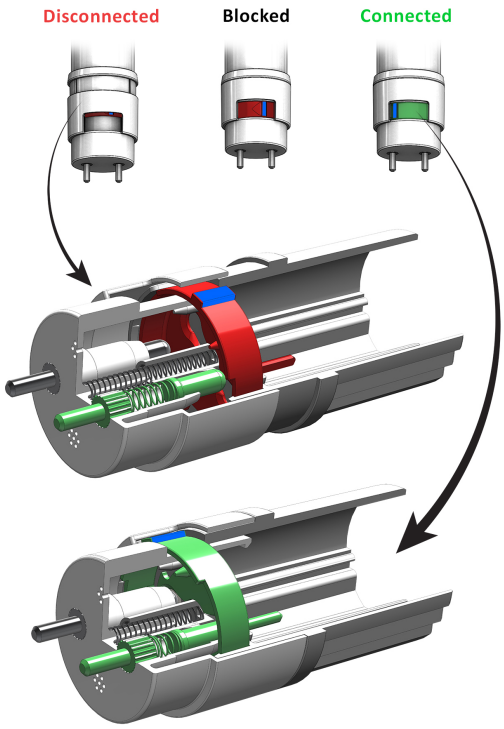

Figure 4: The safety end cap solution solution for a universal tube: a radially directed switch (in the figure this part is coloured red in the "off" and green in the "on" state) which can be turned on by the end-user by pushing against the blue coloured edge and with a release mechanism that is triggered once the length of the tube in the axial direction exceeds a threshold value well before electric contact would be lost.This results in minimal axial moment of force acting on the lamp-holder and no fatigue of the switch over its life time and eliminates the chance of arcing.

Market developments

Late to make the transition

In general the market of LED tubes until now develops slowly as compared to other LED markets. Several reasons may be the cause for this. First, fluorescent tubes are amongst the most efficient legacy light sources and as a result it took until main stream mid power LED's reached 150 lm/W for full distribution before cost effective propositions with significant energy savings could be developed and then still mostly for T8 and T12, not yet for T5. Second, there is the issue of liability in case the luminaire is rewired to overcome compatibility issues with the ballast or to be able to use a tube that can only function on direct mains. Acknowledging geographical differences, there are regions in the world (such as the EU) where most installers will refrain from rewiring.

Third is compatibility. Quite a few end-users have negative experiences with the actual performance (compatibility) of the LED tubes in the field, mostly on electronic ballasts. Fourth is price, which is mostly a consequence of the fact that the other three issues resulted in relatively low demand.

The solution we present in this paper addresses all of these points and will help to accelerate the transition to LED tubes.

We have built partnerships through a licensing model of the technology described in this paper. We have licensed both well known brands, such as *Opple Lighting* and *LED's Change the World*, as well as a leading ODM/OEM manufacturer, *Sengled*, who is in the position to offer the solution to all players in the lighting market. A portfolio of products is available from these partners. Our overall ambition is no less than to set *the* standard for retrofit linear LED lighting.

The feedback through these partners from the installers and end-users is right out positive and an aggressive cost-down road-map will help to accelerate market adoption further.

Regulatory

There is an interesting additional aspect to the market of linear light sources: RoHS.

This international regulation, which aims to ban hazardous substances from the environment, so far allowed exemptions to the elimination of mercury to fluorescent tubes.

These exemptions are expected to be not extended in the EU in the course of 2018 with effect from 2020 onwards.

As a consequence the category of T8 tubes will rapidly shift to LED tubes, very likely creating an even stronger market demand for universal solutions, because of their ease of use.

Extensions of working principle

Like every new technology, the universal tube technology will follow a road map of innovations driven by market needs. Two such innovations are highlighted below.

AC mains

The basic proposition for universal OneTLED is that retrofit will virtually always work well without any need to rewire or temper with the exisiting luminaire. As such no direct mains operations is required or even wanted.

However, under certain circumstances, the option of direct mains drive may have its virtues:

- When a universal LED is retrofitted, the ballast will have already consumed part of its lifetime. For magnetic ballast this in practice will be hardly of any significance, but for electronic ballasts this may result in ballasts failure well before the end of (economic) life of the LED tube. In that event, rather than replacing the electronic ballast, it can be considered more favourable for the end-user to power the LED tube directly from the mains.
- Some of the newer luminaires are designed for direct mains driven LED tubes only and it is practically desirable to be able to fit them with the same SKU as used for the rest of the building or project.

To cater for these requirements of the market, we have extended the principle described in this paper to arrive at a universal tube with nearly 100% compatibility that also allows for direct mains drive.

Power regulation on electronic ballasts

In certain cases, such as projects financed via its energy savings, there is a need to have an upfront very well known operating power of the tube ballast combination. When we take once again a look at figure 3 we can observe that there is still room for improvement as compared to fluorescent.

The main reason for this is the fact that the power on an electronic ballast is not actively regulated: the LED load is connected passively.

There is a way, known in the patent literature, to improve this by driving the LED load with a switched mode power supply (SMPS) operating at very high frequencies (ball park 1 MHz).

The Si-based switching devices one applies today

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in cost effective SMPS will become far too inefficient at these frequencies.

Recent advances in the maturing of GaN wide bandgap switch devices may open the possibility to apply these highly efficient components in the not too far future delivering to the end-user an operating power of the universal tube with much smaller spread.

Conclusions

The technology is ready and cost effective products are available for large scale retrofitting of linear fluorescent tubes.

Acknowledgment

The work described in this paper has been funded in its entirety, starting in 2013, by Momentum Capital, a Dutch private equity fund.

References

[1] T. Drost, DEKRA Arnhem, private communication May 2018

Water Metering Data Acquisition and Transmission Through Street Lighting Enabled Network

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Abstract

With the advent of digitalisation and connectivity in a sector such as lighting, new paradigms for interoperability between services are generated, which facilitate and improve the citizen experience. The street lighting network, because of its privileged location, can play a determining role.

The street lighting network is visible in the most remote locations and covers almost every inhabited area worldwide. Its privileged position close to residents and thanks to its connection to the power grid not only provides the essential street lighting service, but also acts as the ideal platform from which to support many others.

This is a major challenge given that this network must have a high availability ratio and provide a robust service, for which it is necessary to carry out an adequate deployment. In return, it allows us to have interoperability between the different urban services, to be more efficient in the management of them and to provide them to the citizen with higher quality.

Water supply is one of the most important urban services in a city. Its proper management is a guarantee of water quality, of the sustainability of the service through the optimization of resources as well as a correct quantification and valuation of the cost of said infrastructure.

Currently there are advanced systems for the measurement of water flows, both for human and industrial consumption. Many of these systems incorporate data acquisition and transmission capabilities. However, this is not always easy since these systems often have important limitations such as the use of limited lifetime batteries, the lack of connection to the electricity grid or their location in places of difficult access or in the absence wired or wireless connectivity. All this makes it difficult or expensive to manage the valuable data provided by these systems.

We will describe, through a practical case, how to facilitate the acquisition and transport of data from water meters through the use of a nearby street lighting enabled communications network.

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The lighting network as an urban inter-operable infrastructure and its new role within coming urban services ecosystem.

The street lighting network is visible in the most remote locations and covers almost every inhabited area worldwide. Its privileged position close to residents and its connection to the power grid not only provides the essential street lighting service, but also acts as the ideal platform from which many other services are supported.

Key factors that redefine the new role of the lighting system

Lighting Digital transformation

The arrival of Solid State Lighting (SSL) technology, commonly known as LED, has made possible equipping lighting fixtures with intelligence and connectivity as part of an environment characterized by communication and the interaction of objects via the Internet (IoT — Internet of Things).

To make this possible, the lighting fixture control device (driver or LED converter) has to integrate the capacity to acquire, store and process data via microprocessor-based digital architectures. It also has to offer storage capacity and the bidirectional exchange of this information. The development of new drivers for LED lighting fixtures with significant monitoring and control capabilities, in addition to autonomous operational features, allow very valuable data to be acquired for the efficient management of urban lighting. This makes it possible for each outdoor lighting fixture to become a data server (data-enabled lighting).

Wireless connectivity.

Moreover, the current available IT technologies have also allowed the miniaturization and energy optimization of the communication devices and therefore the reduction of power consumption, making possible the widespread use of devices even if powered by batteries.

The extension of the coverage of wireless communications networks (mainly mobile telephone network), together with an important rationalization of the costs derived from its use, makes possible the universalization of access to wireless communications both locally and worldwide.

These technologies and existing communication systems are in continuous evolution, increasing the aforementioned improvements, making them more attractive and useful to be used to transport the growing demand for data exchange.

This rapid and continuous evolution of technologies makes it essential to adopt flexible, open and inter-operable philosophies when designing and building the architecture of the systems that use them, such as the management systems of urban services.

The new double role of street lighting.

The digital and connected new street lighting infrastructure is thereby turned into a service: apart from being light poles, the lighting fixtures may act as infrastructure nodes of the Internet of Things (IoT).

This new potential capacity of the street lighting infrastructure provides a double role in the framework of the urban services ecosystem.

First, it keeps its original and principal role of providing effective and efficient lighting. This functionality is enhanced by the ability to interact with their environment through sensors as well as through an individualized control of each of the lighting fixtures provided by the CMS which allows an immediate adaptability to the light demand on each time and location.

However, a new secondary role appears, but no less important, which is to serve as a connectivity infrastructure for other urban services. The new role adopted by lighting is given by the addiction of connectivity to each street light, converting the street lights into a data enabled network, making it a very powerful communications network to receive and transmit information (low rate data communication) in its immediate surroundings. This capacity is extended by the extension and geographical reach of street lighting networks already deployed in all the urban areas and territories worldwide.

This network has the following characteristics or

fundamental qualities as a platform or infrastructure to support other urban services:

- Network with direct and permanent connection to electrical power grid
- Strategic situation raised above the plane where most of the activity in the city takes place
- Close situation near most of the residents and the rest of the service infrastructures

Interoperability of urban services and its quality of service.

The degree of interoperability required by a complex and multidisciplinary system as Street lighting CMS is so demanding that it has to be developed on a customized and integrated basis in order to adapt it to outdoor lighting as well as to other urban services and ensure that it is flexible, adaptable, inter-operable, replicable, robust and secure. Furthermore, its development has to be accompanied by an integrated level of service for the end user, including advisory services and planning, project engineering for each installation, training and commissioning, technical support and maintenance in addition to applications that add value.

On the other hand, the current state of technology allows to provide intelligence and connectivity to virtually any device of daily life.

Each service center either electric, water, waste management or traffic has become a potential and useful data generator.

The technology allows the grouped control of networks and information points in a centralized way.

It makes possible taking more accurate decisions (Data Driven Decisions) based on more available information.

It is capable to process larger quantities of information from different sources and processed in parallel through systems interconnection. This feature leads to an improvement in the quality of service as well as an improvement in the user experience.

Some of the main benefits provided by this new way of managing services are: Real time information and reaction; adaptive and reactive systems to a challenging environment; management transparency; comfort, control and safety increase for citizens and increase of services user's experience.

Analysis tools and network design algorithms as a service reliability guarantee

All these advantages previously discussed lead to a series of technical challenges to be solved like the system's high availability ratio as well as the correct design and deployment of communications network.

In order to face and overcome these technological challenges, we have several tools that we must put into practice when developing such kind of engineering projects: Analysis tools, Design tools, Network tools and Remote and on-site deployment tools.

Main analysis tools used are:

- Channel modeling tools
- Network analysis tools
- Routing protocols
- Probability and failure rate analysis

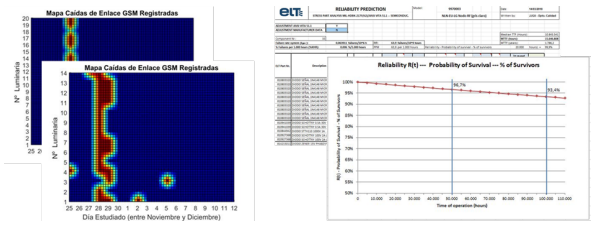

Figure 1: STELARIA System sample analysis tools.

With regards to the design tools, it is recommended to use: Mesh topology; Redundant design; optimization algorithms and heuristic algorithms.

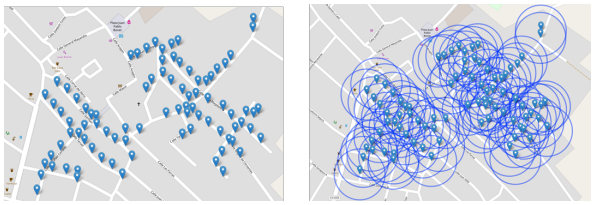

Figure 2: STELARIA System sample design tools.

Finally, remote and on-site deployment tools are key factors in order speed up the deployment of

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the installations as well to correct possible deviation detected from the original network projection.

In case of STELARIA, for instance, it is used STELARIA CityScope which is a PC software based control console using RF only communication which is capable to control and monitor every key lighting related and networking related parameters of every street light (node). By means of using this system it is possible to check link reliability between nodes, radio signal intensity etc.

Water metering data acquisition and transmission through street lighting enabled network

Following the above principles, an exercise has been done to evaluate in a practical way which is the most suitable way to integrate water metering devices of a reputed European manufacturer which already incorporate wireless data exchange capabilities.

The integration of this system of meters has been made with STELARIA, the remote wireless street light management of the Spanish company ELT. Let's see briefly what is the network architecture of both systems, this will help us to understand how next analysis and its corresponding conclusions were made:

STELARIA Street lighting wireless CMS system architecture.

Let's summarize the network architecture of STELARIA which is used to manage and control street lights. STELARIA does it through a network of IPv6 nodes adapted to a local mesh network that is wireless, multi-hop, end-to-end on the ISM (Industrial, Scientific and Medical) sub-GHz frequency band. The network protocol used is based on 6LoWPAN (IPv6 over Low power Wireless Personal Area Networks), the standard and inter-operable protocol proposed by the IETF (the Internet Engineering Task Force) for WSN (Wireless Sensor Network) sensors. The 6LoWPAN protocol stack is able to establish compatibility with the TCP/IP protocol in IPv4/IPv6

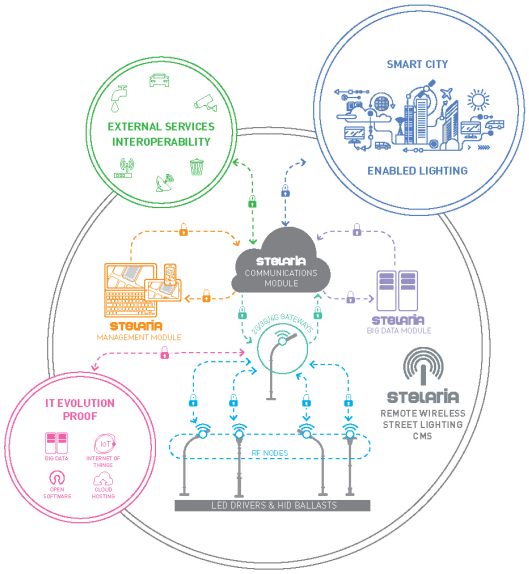

Figure 3: STELARIA Street Lighting CMS.

networks that have the limited processing capacity and memory of microprocessor-based systems, enabling a link to each lighting fixture from the application based on IP routing. On the physical and MAC (Media Access Controller), on the radio device, 6LoWPAN is subject to the IEEE 802.15.4 standard, and the application layer used is CoAP (Constrained Application Protocol).

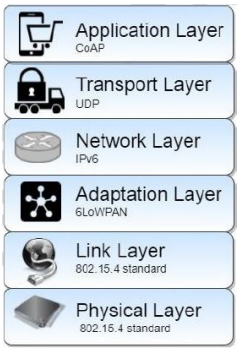

Figure 4: STELARIA Street lighting CMS Stack layers.

Digital wireless water metering system architecture.

The studied water meter system and subject of this project incorporates an advance digital water metering technology as well the capability to transmit data records wirelessly through a mesh network radio link using 868 MHz non licensed ISM band created according to the IEEE 802.15.4 standard.

As you can see in Figure 5, the application layer has a proprietary RIAC protocol, defined and known by the manufacturer of the water meter system. This information can be also transferred to the counter part (street lighting CMS) for integration purposes.

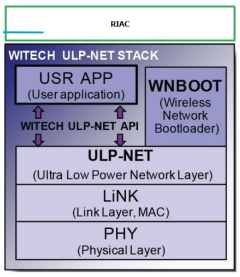

Figure 5: Water meter stack layers.

However, the rest of the network stack layers are provided or belong to third party and are based on a commercial physical device of a different brand (Witech). This means that this information is fully unknown or difficult to obtain.

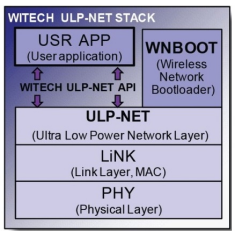

Figure 6: Water Meter unknown proprietary protocols stack layers.

The architectures previously described lead us to evaluate the two most feasible integration possibilities between both systems:

1. Integration at the physical layer level.
2. Integration at the application layer level.

At this point it is worth remembering what is the structure of the OSI stack:

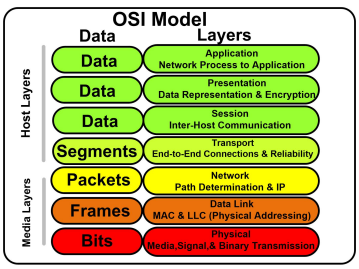

Figure 7: OSI Stack layers.

The Open Systems Interconnection model (OSI model) is a conceptual model that characterizes and standardizes the communication functions of a telecommunication or computing system without regard to its underlying internal structure and technology. Its purpose is the interoperability of diverse communication systems with standard protocols. The model partitions a communication system into abstraction layers. The original version of the model defines seven layers.

Integration at the physical layer level.

Let's analyze what would be the way to perform this integration at the physical layer level.

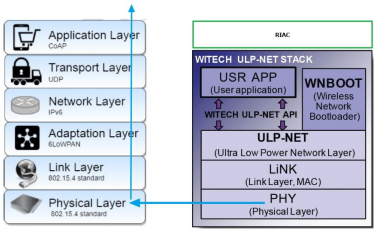

Figure 8: Systems integration at the physical layer level.

In the block on the left of the Figure 8, the layers structure of STELARIA Street lighting CMS network stack is represented.

In the right block we can see the layers structure but of the water meter control system with which we were trying to integrate.

Integration at the physical layer level is the first option to assess, since it would be the most efficient way to do it. A priori this would be possible since both devices share the same physical layer (frequency and modulation).

However, this integration at the physical layer level is not feasible since the network and transport layers of the water metering network are implemented through an unknown proprietary protocol provided by a third party. This makes it impossible, in fact, to perform such integration through physical layer since it is not possible to know the existing implemented protocol.

All this leads us to assess the following possibility of making such integration.

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Integration at the application layer level.

Next we represent what would be the integration structure between both systems through the application layer.

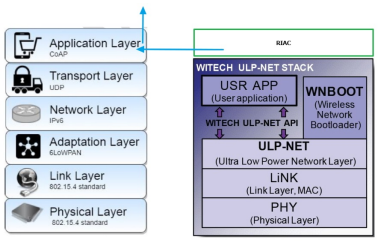


Figure 9: Systems integration at the application layer level.

In this case, the manufacturer of the meters is fully aware of the protocols used in the application layer (RIAC) and it is able to share it to the other party (STELARIA developers) in order to make it compatible.

The integration between both systems can be done in this way at the application layer level, without great difficulty. However, in order to do this, it would be also necessary to incorporate the existing networking hardware of the water meters on the street lighting system (STELARIA nodes). This hardware incorporates the physical, transport and network layer used by the water meters and provided by a third party.

This lead to several important consequences:

- Need to redesign the communications node STELARIA to create new specific compatible model with mentioned water metering networking architecture and only with this particular one. This leads also to a low versatility of resulting system as it can only operate water meters from one company.
- Low interoperability of the system as it is linked to a proprietary protocol, thus abandoning the concept of an open and inter-operable system.
- Increased costs by having to industrialize again the Street lighting CMS devices and incorporate new additional networking hardware to the already existing one used for street lights network.
- Dependence of a third party provider, which may boost economic and operational risks.

For all these reasons, this option should be discarded and an alternative formula must be found that could keep and open and inter-operable system concept.

To this end, it has been proposed to the water meter manufacturer to discard the integration with the existing water metering model that incorporates proprietary protocols and speed up migration to next generation of water metering sharing same physical layer (IEEE 802.15.4, 868 MHz) but implementing existing open standards based protocols for metering networks like Wireless-MBUS. This new generation of water meters are being also produced by the water metering company.

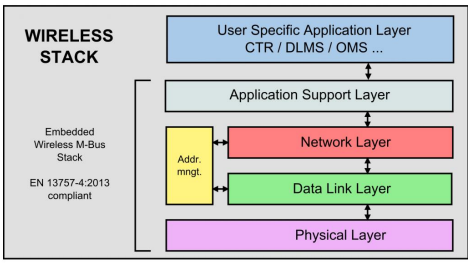


Figure 10: Wireless MBUS Stack layers.

In this way, it is not necessary to make any modification in the physical layer of the STELARIA communication nodes (street lights) or in the water meters.

To make interoperability and communication between the devices possible, it is simply necessary to incorporate the implementation of Wireless MBUS protocol to the physic layer by modifying the STELARIA firmware adding and not eliminating pre-existing protocols already implemented and optimized in the STELARIA stack for the street lights networking.

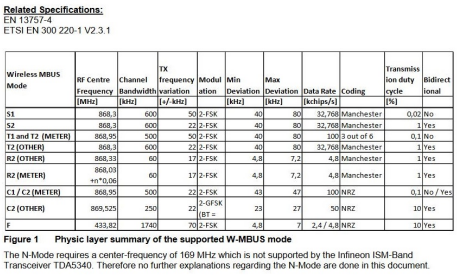
In this way we should achieve an integration of the water meter system with the lighting system in a simple, economical and open way, valid for all those meter systems that use the widespread Wireless-MBUS open standard.

Integration at the WMBUS physical layer level.

To overcome the found problems in the two previous options, maximize communication efficiency as well as minimize industrial cost while maintaining the concept of open and inter-operable systems, the viability of an

integration through WMBUS (Wireless MBUS) has been also analyzed. This standard is commonly used by the water and gas metering devices industry.

Wireless-MBUS (specified in EN 13757-4) is a radio variant of MBUS (Meter-Bus) which is an European standard (EN 13757-2 physical and link layer, EN 13757-3 application layer) for the remote reading of gas or electricity meters.



Related Specifications:
EN 13757-4
ETSI EN 300 220-1 V2.3.1

Wireless MBUS Mode	RF Centre Frequency [MHz]	Channel Bandwidth [kHz]	TX frequency variation [+/- kHz]	Modulation	Min Deviation [kHz]	Max Deviation [kHz]	Data Rate [kchips/s]	Coding	Transmission duty cycle [%]	Bidirectional
S1	868,3	600	50	2-FSK	40	80	32,768	Manchester	0,02	No
S2	868,3	600	22	2-FSK	40	80	32,768	Manchester	1	Yes
T1 and T2 (METER)	868,95	500	50	2-FSK	40	80	100	3 out of 6	0,1	No
T2 (OTHER)	868,3	600	22	2-FSK	40	80	32,768	Manchester	1	Yes
R2 (OTHER)	868,33	60	17	2-FSK	4,8	7,2	4,8	Manchester	1	Yes
R2 (METER)	868,03 +n*0,06	60	17	2-FSK	4,8	7,2	4,8	Manchester	1	Yes
C1 / C2 (METER)	868,95	500	22	2-FSK	43	47	100	NRZ	0,1	No / Yes
C2 (OTHER)	869,525	250	22	2-GFSK (BT =	23	27	50	NRZ	10	Yes
F	433,82	1740	70	2-FSK	4,8	7	2,4 / 4,8	NRZ	10	Yes

Figure 1 Physic layer summary of the supported W-MBUS mode

The N-Mode requires a center-frequency of 169 MHz which is not supported by the Infineon ISM-Band Transceiver TDA5340. Therefore no further explanations regarding the N-Mode are done in this document.

Figure 11: Physic layer summary of the supported Wireless MBUS mode.[1]

M-Bus is also usable for other types of consumption meters.

The M-Bus was developed to fill the need for a system for the networking and remote reading of utility meters, for example to measure the domestic consumption of gas or water in domestic use. This bus fulfills the special requirements of remotely powered or battery-driven systems, including consumer utility meters. When interrogated, the meters deliver the data they have collected to a common master, such as a hand-held computer or to the closest external network node, connected at periodic intervals to read all utility meters of a building.

Since the M-Bus is not a network, and therefore does not, among other things, need a transport or session layer, the levels four to six of the OSI model are empty. Therefore, only the physical, the data link, the network and the application layer are provided with functions.

Conclusions

A system integration such as the one described above is capable of enhancing the management of street lighting infrastructures to the maximum degree possible of smart lighting.

Each outdoor lighting fixture becomes a data server (data-enabled lighting). The Street Lighting infrastructure thereby turns into a service: apart from being light poles, the lighting fixtures act as infrastructure nodes of the Internet of Things (IoT).

The communication drivers and network architecture of a Street Lighting CMS system as described facilitate the incorporation of additional sensors and supports the installation of other communications infrastructures or other services, including the management of water meter among others.

The feasibility of integrating a wireless measurement system with the street lighting network is possible and desirable, although it is conditioned by the choice of technology in both systems. The use of protocols based on open standards at the physical layer level is mandatory in order to minimize the costs of such integration and keep a open and inter-operable system concept.

[1] This description of PHY Wireless MBUS has to be seen as a summary out of the Wireless MBUS and ETSI description

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Luminaire Efficiency | A Proposal to Think Different

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Abstract

LED-technology is being utilized in more and more areas. Tunnel lighting for example is an extensive field for the application of LED-technology especially in countries with alpine terrain, like Austria and Switzerland.

When designing optical systems for tunnel luminaires many criteria must be kept in mind: a lighting design must reach requirements regarding homogeneity, luminance and threshold increment, and still handle the challenging environmental conditions that are found in tunnels. With the increase of LED efficiency also luminaire efficiency is an important benchmark for the assignment of most public contracts, especially since this value is understood well by non-lighting related professionals. Minimum values are now even defined in public regulations like the Austrian regulation PlaPB 800.562.1000 of ASFINAG (the Austrian infrastructure corporation)[1]. Unfortunately, the focus on this specific value easily leads to wrong conclusions regarding energy saving as it only considers a single luminaire instead of the whole lighting system. Clearly luminaires without any specific optical system can perform better in terms of luminaire efficiency compared to luminaires with specifically designed lenses. Nevertheless, the overall energy management of a tunnel lighting system is more sustainable when luminaires are used whose optical systems have been optimized for that purpose.

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Introduction

Some thousand kilometers of tunnels are already used in Europe (data of the year 2016: 6600 km in use, 2100 kilometers were under construction or planning [2]). A big part of these tunnels is still equipped with conventional lighting technology. Nevertheless, more and more operating companies choose LEDs as their desired technology, whether for new projects as well as for refurbishment projects. The advantages are clear: the closure of tunnels is a very cumbersome process, that is avoided if somehow possible. Here, the LEDs stand out with their high life-time and reliability.

Since tunnels are mostly operated all day long, efficiency is an important topic as well. 62% of the consumed energy in a tunnel is used for illumination. Measurements in Switzerland show, that 15–30% of the energy consumption for lighting can be saved by a simple 1:1 refurbishment of NaH-lamps. However, in this case observations showed a significant rise of the luminance of the road, which was not necessary. Much better values can be achieved by adapting the whole lighting layout of a tunnel, especially if compared to other measures like adapting the color of the walls. According to estimations there could be energy savings for lighting of around 50%, which would mean a decrease of energy consumption of about 20–30% for the whole tunnel[3].

Trying to reduce the complexity in the decision-making process when comparing the different luminaires provided by the market, minimum values for luminaire efficiencies were defined for what is thought to be a guarantee for a high efficiency of the entire system. Unfortunately, this leads to wrong conclusions easily, since only a single open distribution luminaire is considered.

Specifications for Tunnel Lighting

The CIE88-Guide for the Lighting of Road Tunnels and Underpasses is the main regulation for tunnel lighting and reference for many national guidelines. It divides the tunnel in three distinct zones namely the threshold zone, the transition zone and the interior zone. The length of the threshold zone is defined by the speed limit in the tunnel. The threshold zone is the zone where the driver's eye adapts to the tunnel, hence higher luminance values are required. The transition zone allows a smooth transition between the threshold zone and the interior of the tunnel. Typical values for the required luminance are around 150–600 cd/m^2 for the threshold zone and 2–6 cd/m^2 for the interior zone.

The CIE88-Guide refers more on the values for and luminance that must be achieved with the illumination than on the light source. Similar guidelines can be found in national standards. Usually no specific indications regarding the light source are made in these national standards, but more and more guidelines refer to LED-lighting. To name a concrete example for such a national guideline: *The Planning Manual for Tunnel-Lighting of the ASFINAG (Infrastructure corporation for the management of motorways and express roads in Austria), PlaPB 800.562.1000* [1] distinguishes between three different classes of equipment for tunnels with LED-equipment: Standard, Comfort and Premium. The Standard Tunnel requires at least 105 lm/W for a whole luminaire (at RA $\geq$ 70, and color temperature 4500 to 5500 K), whereas the classes Comfort and Premium require 100 lm/W at RA $\geq$ 80 and color temperature 4500 or lower. These are the minimum values that must be fulfilled so that a luminaire can be used on Austrian highways.

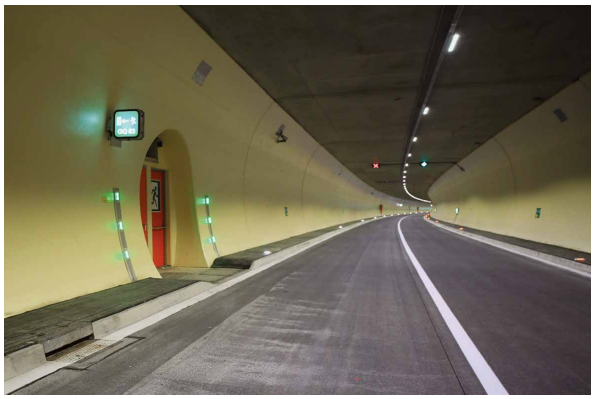

Figure 1: Example of a tunnel of the class *Comfort*.

Apart from that, other requirements need to be fulfilled with LED-lighting in Austria: The uniformity along the roadway must be between 0.55 and 1, depending on the class of equipment and hazard class of the roadway. The TI (Threshold Increment) must be below 10, for premium tunnels even below 6.

Apart from these general requirements in national guidelines most of the time more detailed requirements are mentioned in specific tenders,

here again the luminaire efficiency is a decisive criterion.

For countries with no concrete efficiency mentioned (e.g., Switzerland) specific details regarding efficiency and other luminaire related parameters are almost always specified in tenders.

Optical systems

The environmental conditions in tunnels are very challenging. Emissions from cars and humidity create a harmful mix that can damage many materials. Therefore, special materials like glass must be used since normal plastic materials are not resistant enough to withstand the contagious environment. This leads to basically three different types of optical systems for the application in tunnels which are used by different manufacturers:

LED with or without a reflector plus a cover glass

The simplest solution is a LED and a cover glass. This kind of technical solution can also be combined with a reflector. The light output ratio of these luminaires can be very high when special cover glass is used. The disadvantage of this solution is the very limited possibility in shaping the light distribution. This results in a large amount of light that does not reach the required area, but hits the part of the tunnel, that does not need to be lit up.

LED with a plastic lens plus a cover glass

Most current solutions use plastic lenses to shape the light distribution. In front of the plastic lenses a glass cover must be applied, since the environmental conditions in tunnels are very harsh. Normal PMMA-and PC-optics are not able to withstand these atmospheric impacts, for example air pollution and high salinity.

This kind of luminaires is in general less efficient than luminaires without plastic lenses, since the light must pass through four optical interfaces where efficiency is lost. Especially rays at very flat angles are highly affected by Fresnel loss in luminaires with cover glasses. This effect can be seen on the light distribution (see Fig. 2) where the rays on angles at around $\gamma = 70°$ are absorbed much stronger than rays at $\gamma = 0°$.

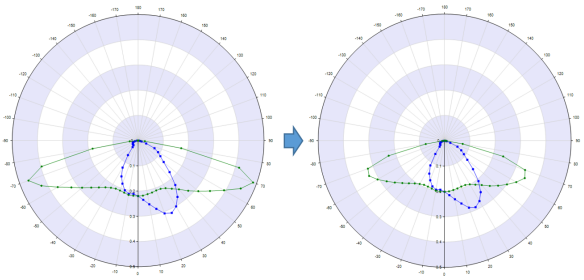

Figure 2: The left image shows a light distribution of one LED plus a lens. In the light distribution on the right side an additional cover glass is used. This effects a significant change of the light distribution especially at high values of γ.

Since the requirements are different for the various zones of a tunnel (threshold zone, transition zone and interior zone) different lenses are used for every zone of the tunnel.

LED with a glass lens

The preferred solution of Swareflex is the usage of glass lenses to shape the light distribution. The high resistance of glass to all kind of atmospheric influences makes it possible to forego the glass cover. This means a reduction of optical interfaces which results in an improved light output ratio. This improvement can be seen especially on the light rays that leave the luminaire at very flat angles.

Figure 3: Swareflex E04 lens: a glass lens optimized for the interior zone of a tunnel.

Nevertheless, a solution with open LEDs and cover glass can reach higher values for light output ratio since a specially treated cover glass can be used, which leads to a very high

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transparency. This kind of treatment is not (yet) possible on freeform lenses.

Lighting design in tunnels

The arrangement of the luminaires in a tunnel must be according to the adaption curve of the luminance in tunnels.

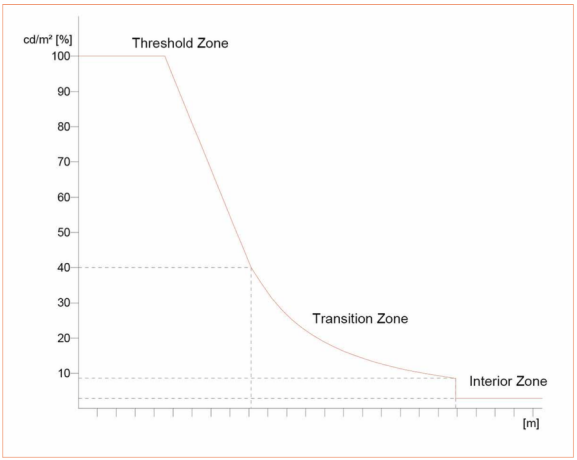


Figure 4: The arrangement of the luminaires in a tunnel must be made in such manner, that the luminance of the road follows this curve. The highest value of the luminance can be found in the beginning of the threshold zone. This value is called L_{ef}. [4].

Therefore, the lighting design must be divided into threshold zone, transition zone and interior zone. The threshold zone allows the adaption of the driver's eye to the lower brightness in the tunnel compared to the outside. Its length is defined by the speed limit at the entrance of the tunnel. In the transition zone the luminance level on the road is steadily reduced so that a smooth adaption from the entrance luminance levels to the lower interior levels is made possible.

To fulfill all kind of requirements not only the number of luminaires is adjusted in the different zones, but also the light shapes. In the threshold zone extremely asymmetric light distributions are used in a counter-beam configuration whereas in the interior zone more symmetric lenses are used.

This division of the different zones in the tunnel is made in the following investigation as well. The comparison shows the results of the lighting design for different tunnel projects with luminaires of Swareflex and its competitors.

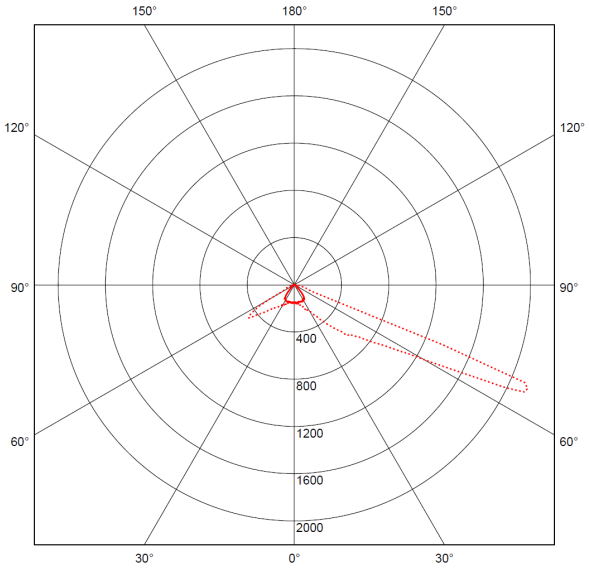


Figure 5: The Swareflex A07-lens creates a very asymmetric light distribution (depicted in the picture) which is ideal for the entrance zone (threshold zone) of tunnels.

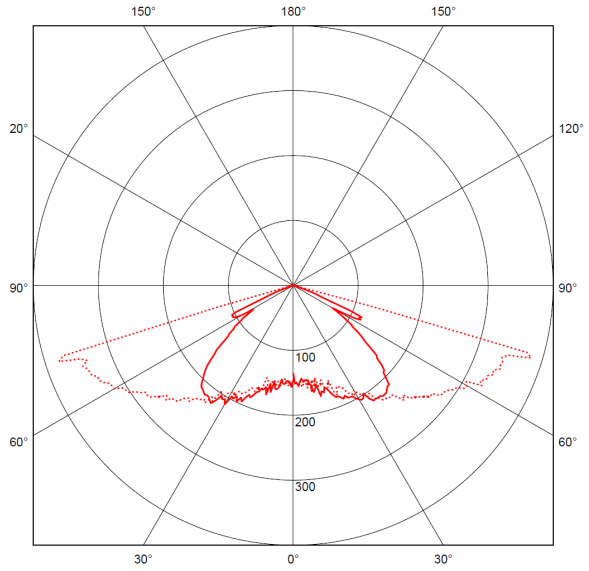


Figure 6: The Swareflex E04-lens creates a light distribution (depicted in the picture) for the interior zone of tunnels.

Threshold zone

Regarding the threshold zone we look at the project *Bergisel*, a bypass tunnel on the highway next to the city of Innsbruck in the Austrian alps. Here we compare the lighting design of a luminaire with Swareflex A07 glass lenses and different competitors: competitor 1 with a NaH-lamp plus a reflector and competitors two and three with lenses and a cover glass. The street has two lanes and thus a width of 7.50 m, the mounting height is at around 6.20 m and the length of the threshold zone is 189 m. The

luminance coefficient of the street is 0.07 cd/m^2/lx which corresponds to streets of the class R3. The comparison was made in such manner, that the luminance of the first part of the entrance zone fulfills the requirements of 145 cd/m^2. This luminance value is named L_{ef} in various regulations. The results of the lighting design can be seen in Fig. 7.

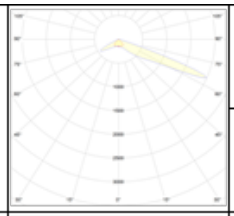
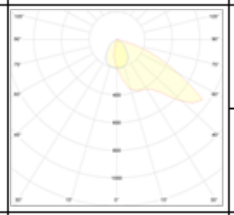
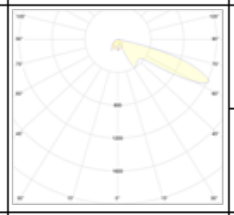
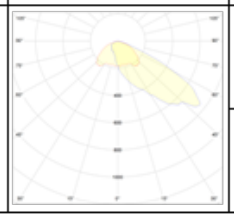
luminaire with glass lenses		efficiency (lm/W) 65
		installed power (W) 27800
luminaire with a NaH-lamp		efficiency (lm/W) 97
		installed power (W) 33500
luminaire 1 with plastic lenses		efficiency (lm/W) 101
		installed power (W) 27600
luminaire 2 with plastic lenses		efficiency (lm/W) 112
		installed power (W) 37000

Figure 7: Comparison between different luminaires applied in the threshold zone of a tunnel: The difference in efficiency does not translate into energy saving in the tunnel. If the most efficient luminaire is used (*luminaire 2 with plastic lens* — 112 lm/W) then much more luminaires must be mounted in comparison to the least efficient product (*luminaire with glass lenses* — 65 lm/W). A lighting solution with this less efficient luminaires with glass lenses is significantly less power consuming than a solution with the very efficient *luminaire 2 with plastic lenses*.

The solution with the Swareflex A07 lens has an efficiency of just 65 lm/W. Therefore it is worse than the other competitors' solutions. The best competitor in terms of efficiency is competitor three which has an efficiency of 112 lm/W. Nevertheless, the consumed power of this kind of luminaire is much higher than the Swareflex A07 solution, since a higher number of luminaires must be installed to achieve the same luminance on the road. Only luminaire 1 with plastic lenses is comparable to the luminaires with glass lenses. And even here the difference of the consumed power is small even though the difference in efficiency is more than 35%.

Interior zone

For the interior zone we looked at a standard road with two lanes and a width of 7.5 m. For this zone many companies use luminaires without any lenses since the requirements can usually be fulfilled even without any special kind of optics. As mentioned in the previous chapters these luminaires can have a very high value of efficiency. Therefore, we compare the performance of this kind of luminaire to a luminaire with a special optic. In our hypothetical lighting design, the luminaire without any lens would have a 15% higher efficiency than an optimized Swareflex-product. This difference should be even smaller in reality. The results of this comparison can be seen in Fig. 8.

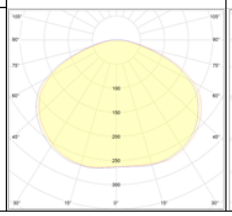
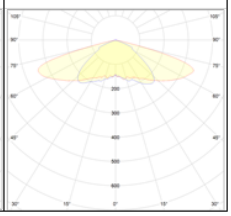
	luminaire with LEDs only	luminaire with glass lenses
efficiency (lm/W)	137	116
average luminance on the street	3.94	4.94
Uniformity U0	0.52	0.54
Uniformity UI	0.89	0.90
TI	8%	8%
luminance on the walls cd/m²	6	6
illuminance on the street (lx)	82	80
illuminance on the wall (lx)	45	37
light distribution		

Figure 8: Comparison between a luminaire without any optic and a luminaire with optimized glass lenses. The difference in efficiency does not translate into energy saving in the tunnel. With the same power consumption, the luminance on the road would still be 25% higher using the solution with the lens.

Once again one can observe that the difference in efficiency does not translate into energy saving in the tunnel. With the same power consumption, the luminance on the road would still be 25% higher using the solution with the lens because all rays that leave the luminaire hit only the area that is important for the task of security. The luminaires without any optical systems generate a lot of light, but a lot of it hits areas that are not of interest.

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Lighting design in tunnels

We believe, a possible way to improve the system for rating the efficiency of luminaires in tunnels could be the introduction of an alternative parameter. This parameter would need to be easy to understand, so that people not familiar with road lighting can work with this value as well.

Frey et al. showed in [3] that the energy consumption of a tunnel correlates with its length. Therefor they are proposing a general key value *energy per kilometer per year*, which they are using for benchmarking tunnels in Switzerland. Analog to that, a factor "performance per kilometer" for the illumination could be used to describe the ability of luminaires to light up a certain tunnel element. To be able to use such a factor, certain parameters must be defined for example reflectivity of the wall and the reflectivity of the road. Another possibility could be the inclusion of this values into the parameters. Such a complex power density P_d could be the following:

$$P_d = \frac{\text{power consumption}}{\text{length}_{\text{tunnel}} * \text{width}_{\text{tunnel}} * \text{luminance}_{\text{road}}} \quad (1)$$

Since we have made the comparison of our luminaires with similar luminance, length and width, these parameters correlate linearly to the power consumption in our example for the entrance zone.

Another possible solution could be the introduction of a parameter, that describes the amount of light, that hits the effective area that must be illuminated. The effective area would be the road and partially the wall of the tunnel to a certain height. This criterion would be very easy to understand and describes the quality of a light distribution very well. Combined with the LED-efficiency this would allow good judgment of the effectiveness of the lighting solutions. The advantage of this solution is that no standardized reflectivity must be defined.

Conclusions

In this conference contribution we have shown that LED lighting helps to reduce the energy consumption in tunnels significantly. To find the most sustainable solutions some things need to be kept in mind: Only a concrete lighting design can help to find the best way of equipping a tunnel, a 1:1 refurbishment does not lead to an ideal solution since a lot of potential for energy saving is not used.

Furthermore, the efficiency of the luminaire is not a good value to describe the ability of a luminaire in a tunnel to safe energy, since it gives no information about how much light reaches the reference plane. Luminaires without any specialized optical systems can have very high efficiency levels, but show poor performance in the interplay with other luminaires.

In addition, we plea for the introduction of alternative parameters which would allow decision-makers to identify the most sustainable solutions more easily. For this, we have introduced different proposals that could allow such an assessment. We hope, that such parameters find their way into tenders and replace the criterion of efficiency which often leads to bad solutions in term of energy saving, how we have shown in this conference contribution.

References

[1] Technisches Planungshandburch der ASFINAG, PlaPB 800.562.1000, Version 3.01, affective from 01.02.2018

[2] Bundesministerium Verkehr, Innovation und Technologie. press release. 10th of June of 2016, https://infothek.bmvit.gv.at/oesterreich-land-der-berge-und-der-tunnelbauer/.

[3] Frey, Samuel & Riess, Ingo & Welte, Urs & Wildi, Peter. (2016). Verbesserung der Energieeffizienz von Strassentunneln.

[4] Herzig. (2017). Technology Challenges in Professional Tunnel Lighting Applications (Article). LpR 61, p 66.

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EDITORIAL CALENDAR 2019

ISSUE N°	IN THE SPOTLIGHT*/**	ABSTR. DUE	ARTICLE DUE	ONLINE PUB.	PRINT PUB.	PREFERRED ISSUE (MARK)
71 Jan./ Feb.	**TECHNOLOGIES FOR HEALTH & WELL-BEING** Efficient lighting has become a prerequisite. Ongoing discussions question whether efficient lighting is also healthy lighting and if it supports well-being. Findings, technologies, designs and applications supporting health and well-being are the focus of this issue.	Oct. 15, 2018	**Oct. 22, 2018**	Jan. 15, 2019	Feb. 01, 2019	
72 Mar./ Apr.	**FUTURE PROOF SYSTEMS & SOLUTIONS** Most buildings are constructed to last at least four decades. Owners and operators are only willing to invest in long lasting future proof solutions for the infrastructure. The topic of this issue is the question of if and what future-proof solutions and technologies are available.	Dec. 17, 2018	**Jan. 04, 2019**	Mar. 15, 2019	April 01, 2019	
73 May./ June	**DISRUPTIVE TECHNOLOGIES & APPROACHES** A good part of the lighting industry suffers from high production costs – especially in Europe and the US. New concepts, designs, materials and manufacturing methods may be advantageous. This issue reveals the most ingenious approaches.	Feb. 25, 2019	**Mar. 04, 2019**	May 15, 2019	June 03, 2019	
74 July/ Aug.	**TECHNOLOGIES FOR SPECIFIC TASKS & APPLICATIONS** Light is not only used for illuminating rooms and open spaces. The applications of LEDs are manifold. This issue acknowledges the importance of LED light sources in automotive, horticultural, medicinal, cosmetic, and environmental applications, to name just a few.	April 24, 2019	**May 06, 2019**	July 16, 2019	Aug. 01, 2019	
75 Sept./ Oct.	**ENVIRONMENTAL FRIENDLY DESIGN & ENGINEERING** The EU Commission supports the move towards a more circular economy. Additionally, research demonstrates that artificial light may negatively affect the environment. Technologies, designs and solutions that recognize these two aspects are addressed in this issue.	June 26, 2019	**July 05, 2019**	Sept. 02, 2019	Sept. 24, 2019	
76 Nov./ Dec.	**TECHNOLOGIES FOR VISUAL PERFORMANCE & COGNITION** Some research results suggest that the spectral properties of a light source have great influence on visual performance, cognition and arousal. But it is more than just the spectrum that counts. This issue presents supporting concepts, technologies and solutions.	Aug 06, 2019	**Aug 26, 2019**	Nov. 15, 2019	Dec. 02, 2019	

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Lighting Quality & Testing

486 How to Tackle the Increasing Complexity at Legislative Compliance
by Jacob Nuesink, DEKRA

492 Aging of Potted LED Modules in Terms of Realistic Conditions
by Thomas Schulz, LUMITRONIX

498 Reliability of New Light Quality Metrics: Challenges and Opportunities
by Dr. Benoit Hamon, Pi Lighting

506 Destroy in the Lab to Last in the Field – LED Robustness, Reliability and Life Time Testing
by DI Alexander Wilm, OSRAM Opto Semiconductors

512 Temperature Profiling of Secondary LED Optics by Infrared Thermography
by Dr. Peter W. Nolte (NOMINEE: LED professional Best Scientific Paper Award 2018), Fraunhofer Application Center for Inorganic Phosphors

518 Light Flicker: A Reasonable Measurement Method in View
by DI Peter Erwin, Der Lichtpeter

How to Tackle the Increasing Complexity at Legislative Compliance

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Abstract

Design of luminaires is becoming easier due to the use of standard modules. Still the design of optics and the mainly performance related parameters are considered the challenge. But is that all?

The world is changing at a rapid pace. We saw the introduction of several new standards and pieces of legislation in 2016/2017. In 2018 the developments will continue to go at a fast pace. Not only will we see a new Energy related products regulation, the so called “one lighting regulation” but also other directives and regulations are coming into force or are already in force (by September).

Many of those are not the standards requirements that we had to deal with till now. The new privacy directive will have impact also on product design and for example the cybersecurity regulation will also have a serious impact on lighting design.

The implications on product design and approbation procedures are serious. Many companies are only focusing on the current and very basic directive. Only few companies are already looking at the implications that they have to deal with future applications.

The main challenge for the industry is how to create modules that will allow for easy product design. Helping those smaller niche companies to implement their legislative approbation process. Smaller niche manufacturers have the challenge to be compliant and still be able to provide products that are in compliance with legislation.

How to do this? First, we will make quick dive into the history and how we came to where we are now. Than what is/has changed in the last years. Mainly the introduction of smart in Lighting has started the many complicating factors that have to be tackled. In the end, it is all doable if we tackle the issue with a carefully planned approach. It is not so much different as in the past there are only more factors to consider.

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Increasing complexity for product compliance

Struggling with product compliance issues. Is product compliance more complex than 10 years ago? In the 1970's electrical safety was equal to product safety but today that alone no longer covers the requirements. Companies complain about the rules and regulations they need to comply with. The facts. There more rules than in the past. Would we, in the 70's consider safety only, now it is necessary to consider many more factors. Today's products are using increasingly complex technology (and software) and globalization does have its effect as well.

On the other hand positive developments have taken place as well. The European union has drastically simplified market access in the union. The processes to show to compliance are simple. The procedures are highly harmonized. The manufacturer is responsible.

Outside the European union, rules and regulations are more stringent and complex in most other economies. Mandatory approvals do not help to decrease complexity. So which factors do influence those complexities?

Increasing regulations

Over the years, an increase in regulations can be seen. Factors like global warming, attention to our environment, increasing population and scarcity of raw materials, progress in technology, call for new rules and regulations. In Europe for example the RoHS directive that limits the use of certain materials came into effect 15 years ago. Preventing hazardous materials to come in our environment after products become waste. The ErP directive was setup to reduce the energy usage of products. Latest proposals call for implementing measures to helping to create a circular economy. In certain cases Europe followed other nations and in other Europe is ahead in implementing rules and regulations.

Taking a luminaire as example we can see the clear increase of regulations. While 40 years ago a luminaire needed to comply with one standard only addressing the electrical safety todays luminaires need to comply with standards addressing the electrical safety, electromagnetic compatibility, hazardous substances, light emission (mainly blue light hazard), energy efficiency and recycling requirements.

When taken into account the updates of the standards necessary due to the introduction of LED and our increased knowledge, it is clear that lots of things have changed.

Globalisation

In many countries outside of the European Union similar trends can be seen. Unfortunately, many regulations are alike but almost never exactly the same. This increases the compliance burden for the globalized industry. Especially true for countries where there is a mandatory third party certification in place. Arguments for a mandatory certification system are strong. Reviewing product compliance status for directives in the EU like f.e. ErP it becomes clear results are not very good to say the least. Mainly caused due to the lack of market surveillance.

Factors

A short analysis of factors which influence compliance complexity

Political and social

Safety

In Europe the Low Voltage directive is in force for many years. The standards that are used to show compliance like the EN 60598-1 are not only harmonized throughout Europe but around the globe. The only economy not using this standard is North America. UL and CSA standards prevailing in that market. Regrettably, the standardization committees have not been able to harmonize the safety standards in the area of lighting. Other standardization committees in areas like for example power tools have show that harmonization is possible.

The EN standard, outside Europe better known as the IEC standard is a widely used standard, although many countries have their national deviations.

International standards facilitate global trade. Local authorities however may set up additional regulations. These are limiting companies to have easy access to that market. Complex national and

local requirements and regulations, in particular the conformity assessment process creates hassles. Mainly for small and medium enterprises. The might just not have enough knowledge and resources to understand all those differing rules and regulations. Expert organization have comprehensive knowledge of conformity assessments around the world and can help.

Environment

Environment is playing a mayor role nowadays and its importance is expanding. Companies may have their own environmental agenda and best practices but also have to comply with the applicable legislation. The rules and regulations differ per country. On top of that, social pressure, is increasing. Look at for example the Fair trade products.

Public tenders increasing contain requirements on environmental issues. Products need to be reparable products, facilitate life extension and reducing waste. All in an effort to steering towards a zero waste society. Such requirements will have its effects on the design of products and the use of materials. The European Union is currently discussing on how to implement rules enabling a circular economy. Discussions on implementing this in the new ErP regulations for lighting (The One Lighting Regulation) is ongoing and possibly finished at the moment of this publication.

Social return

Investments are more and more also based on factors like social return. The weight of this factor is increasing. Companies that are not able to keep up might lose out. The demands can be stringent, like how many people with a distance to the workplace are employed in the company. Or are local facilities for production used. Especially in case of government investments this is an import step. It steers away from buying only the cheapest product to awarding value to other qualitative issues like the social responsibility of a supplier.

Privacy

Developments in the Internet of Things area are of great concern to our privacy. The General Data Protection Directive, in force since May 2018, impacts also product design. When a product is connected and collecting and transmitting data. It seems like countries are competing in having more stringent rules.

Unfortunately standardization is behind and requirements are presently driven by governments. The European CENCENELEC has just initiated JTC13 looking at developments of standards for data protection, information protection and security techniques with specific focus on cybersecurity Clearly, data don't stop at borders and harmonized standards would facilitate global trade.

Cybersecurity

Data protection and cybersecurity go hand in hand. Can data be accessed and manipulated? Are enough measures taken to protect the system? Can systems be hacked and how can be assured that the chances are kept to a minimum?

With the rapid increase of consumer IoT devices and the low level of security measures implemented, disruptions of the internet a are likely to increase. As shown in the highly publicized Mirai botnet DDos attacks in 2016. The good thing, awareness is increasing and, for critical infrastructure rules, and regulations are in force.

For consumer products however there are almost no requirements and standards. This is of great concern to consumer protection organizations. At present it is not clear if there will be regulations coming into force addressing security for consumer products. The EU has proposed the Cyber Security Certification framework directive last year. It remains however unclear in how far consumer products would be included in the scope of said directive. Clearly, the risk a hacked IoT possess with regards to injury, economic damage, or other form of harm will force regulators to come up with an appropriate set of regulation. Between 2016 and 2017 attacks on IoT devices have risen 600%.

Wellbeing

Latest developments might be Human Centric Lighting. Is this a new invention or simply a new interpretation of existing methods of working? Lets leave that up to the reader. It is clear that more knowledge is developed on issues related to our wellbeing in combination (influenced) with light. Studies have shown that the color and

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intensity of light have an impact on the performance of students in schools. Faster recovery of patients in hospitals when they are subjected to the right lighting. Knowledge must still be further developed. On issues like flicker and glare it is to be expected that more standards will become applicable in the future to enhance our wellbeing.

Technical developments

LED / OLED / Laser

New and upcoming technologies all have their own challenges. Very new developments are far more difficult to implement than existing technologies. For new technologies and their associated risks, standards generally do not exist or at most in the development stage. This means that the time and resources to evaluate these products is much greater than with existing technologies.

This leads to additional hurdles in product conformity assessment. Difficulties in getting product accepted by the market will be increased. With LED this problem has been tackled. Currently standards have been developed and also legislation has been adapted. But for example for laser steered lighting products new challenges lie ahead.

Products versatility, fading boundaries

In the past a lighting fixture and a Wi-Fi access point where 2 separate products. Integrating different functions into one product becomes mainstream. Unfortunately this creates new complexities in product compliance. Standards are generally written to cover a product for example a lighting fixture or a access point but generally not both.

In such cases a more extensive risk analysis needs to be carried out. Possible risks not identified by the individual standards and risks which occur by combining 2 product functions need to be carefully analyzed. The boundaries are fading but fortunately more and more standard writing will change in the future as well. Generic risk based standards are already available but it is interpreting a generic standard has its own challenges as well.

The ease to assemble new products

The ease of creating a new product results in many new innovations. Fact is that many “ready” components (modules) are created. New products can be easily created by assembling different modules. Combining modules however, does not assure that the product complies with all regulations. Two compliant components put together do not necessarily provide you with a compliant end product. A mistake made by many.

Economical

Depletion / availability of raw materials

As already mentioned in the political factors also in the economic sense this factor plays a role. Copper prices have increased significantly over the years. Steel and aluminum prices vary a lot. Slowly raw materials become scarce and expensive. This will push the market toward re-use and recycle. This brings new challenges. For example rules exist on the use of cadmium in products RoHS). When recycled material is used these could in principle be contaminated by now banned sunstances. Would that mean that we cannot recycle? Or should we have exceptions? These are additional complicating factors to the use of recycled materials.

Globalisation

Further globalization is a given for large companies. Increasingly smaller companies are crossing the borders as well. For smaller companies this can n be a challenge. The rules and regulations can be significantly different in other countries than there home country.

Internetsales

With internet the borders are fading. Companies that sell online will have the same issues on product compliance. More stringent rules will come. This will make the sales more complex. A one fits all product will be difficult to design. And is it possible to design a product compliant for a market where only a few sales will take place? For example Amazon will limits sales of a product to those regions where they have their product compliance assured. They do not ship to other regions.

Science

New methods reveal lack in knowledge

The introduction of LED has revealed areas in lighting technology where existing methods (knowledge) where no longer achieving the results that we needed. This is caused by a lack of knowledge in those areas. Slowly the gaps are being filled but also to find new gaps along the way.

Good for our scientific community but making it difficult to design products. Especially where you are expecting that rules might change on the short term. This brings a uncertainty into the development process of new products.

Progress in science provides knowledge on problems not know before

The progress however also brings along opportunities for new products. For example knowing that patients in a hospital recover faster due to better lighting brings a new opportunity for the lighting industry and for the healthcare industry to save on hospitalization costs.

People

Knowledge

Employees are expected to be more versatile. More functions and roles must be handled by one person. Especially in smaller companies this is a challenge. The number of standards, conformity requirements and the differences of regulations in all countries is difficult to grasp. Especially for a company that wants to export to many countries. The speed of development of new products but also of requirements is high making it also difficult to keep track of the changes.

Language

Conformity requirements are generally in the countries native language and not for example in English. A barrier that is also not easy to cross. Would normal text be difficult to rightly interpret, legislative documents are generally even more difficult to understand when not in native language.

Methodical approach to product compliance

Project scoping

Sales area legislative requirements

Selling everywhere is an interesting idea. This is however not easy due to the differences in conformity requirements and regulations globally. Look closely at how many products can be sold in a certain area. Depending on the market size, expected margins, technical differences, possible criteria's etcetera a decision should be made. Every country wants safe and compliant products on their market to protect their citizens. However the way to get there and how to enforce it is different.

Customer expectations

Every customer will have certain performance expectations for products. Of course important for product design. For compliance it is only partly important. It is necessary to establish if the targeted customer group has special certification needs. For example selling street lighting in Belgium; CE marking is sufficient. However if you want to be able to sell fixtures that can be used along freeways, you have to deal with several companies who are responsible for the installation of equipment. They have a special certification needs and without that certificate they will not buy the equipment. There is no barrier to sell in the country according to European legislation but if you want be in a certain niche it can be necessary to have additional certification.

Product specification

Clarify what the product really will be. What are the critical parameters. What is the complete range of the product line are your establishing. Do not narrow it down to much. This will limit your final possibilities to make variations on the product. However having a to general specification might increase the complexity and therewith the needed budget for compliance testing and certification.

Assessment

If the sales areas are clear, an assessment can be made on the conformity assessment and

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legislative requirements to which the product must comply. Find out if there are mandatory certification schemes that needs to be followed or if it is possible to do the conformity assessment on your own responsibility.

The internet provides a great deal of information, larger economies today provide transparency with regards to conformity assessment and applicable legislation. Of course your customer or reseller might be able to provided you the required information. Most of the Expert organizations are members of the international IECEE CB certification scheme. Member countries are obliged to provide all relevant information including national deviations to international standards to facilitate access to markets. Complex issue that might warrant the use of a third party consulting service.

Keep in mind that some customers might “over ask”. A check on the activities of competitors will be a good indication on what is usual for a market. Never the less it is important to make a decision not only based on hearsay and what others do.

Product development

Develop the product with those rules and regulations kept in mind. Keeping a quality control officer in the loop during the design phase is crucial. Time and time again companies design their products, and when finished start to look for conformity assessment services. If the product is rejected a redesign might be needed. The costs will be much higher than if these issues where taken care of in the design phase. Involving a product compliance expert in the design phase is crucial for limiting the final testing and certification efforts.

Third party certification

Following the product development, if required, third party certification can take place. When properly integrated in the design process and, if the certifier was involved in the process, it can be a swift and simple process. However sometimes there are specific procedures that need to be followed that are time consuming. Proper planning in the startup phase of the project can limit this delay and make sure that the time to market is short.

Conclusions

Increased globalization, new conformity assessment rules and regulations, more complex products from a functional point of view create a more challenging field for product compliance.

Increasingly the need for specialized companies arises to assist companies in accessing their specific markets.

Project scoping at the start is the main cost saver for testing and certification efforts but also in limiting time to market and prevent the huge redesign costs when needed to bring a product in compliance.

Essential step is scoping of the project in the design phase. Determination of essential certification but also on “nice to haves” can be a big help to prevent running over budget.

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Aging of Potted LED Modules in Terms of Realistic Conditions

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Abstract

Among other things, the evaluation of methods and systems for encapsulating LED modules led to the question of the expected service life.

Information from manufacturers of chemical components about aging were imprecise and hardly meaningful.

The aim of this study is to investigate different systems and to characterize them with methods that are established in LED technology.

The central question is whether a potted LED module can achieve a lifetime under realistic conditions, which is considered to be common for LED modules. A test based on the LM-80 evaluation will show whether acceptable lifetimes are achieved and whether it seems realistic to use extrapolation such as TM-21.

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Introduction

With the advent of LED technology in lighting industries the topic of service life gained in importance. Aging of LEDs is widely understood. Especially in LED module market, long lifetimes of 50'000 h L70B50 are common. For potted LED modules the lifetime of just the LED cannot be set. The experience of the manufacturers of potting systems is mostly too poor to calculate any lifetimes. For a customer specific project, a potting system must be evaluated which is able to give long lifetime at high temperatures.

Experience allow the conclusion that that the lifetime of a potted LED module is significantly shorter than that of a non-cast LED module.

Method

For this study, a method known from measuring LED modules, was applied. This study was inspired by LM80 test for individual LEDs. The aim was to operate potted modules over a defined period of time and measure them regularly. Due to the demand of operating at high temperatures the heatsinks for the LED modules were designed to get a LED temperature of Tj = 95 °C. The manufacturer of potting compounds recommended five different materials. Therefore, six groups were operated to investigate their aging. One group was the reference group with the same LED modules, same heatsink, but without potting. All modules were driven by a constant current of 350 mA. Temperatures were measured using a FLUKE Ti32 thermal camera. The optical measurements were done in an integrating sphere IS-1800 with a spectroradiometer OL-770 by Optronic Laboratories Inc. Thermal measurement were done in the beginning to design the heatsink. Contrary to the rules in LM80, only 10 modules were sampled per casting type. Tendencies will be recognizable without completely losing their statistical character.

The LED modules were operated for 10'000 hours and optical measurement was done every 1'000 hours.

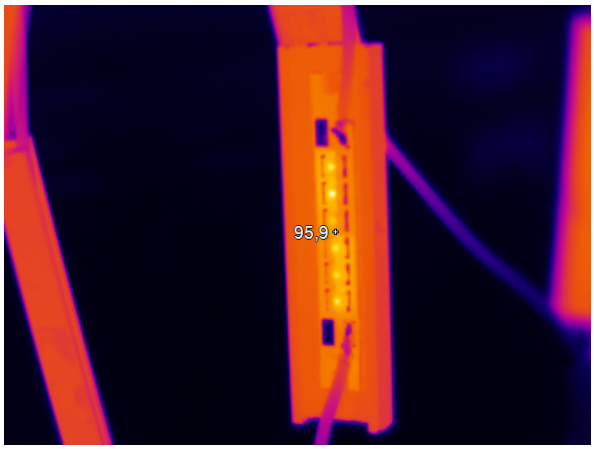

Figure 1: Thermal measurement at an uncovered LED- module.

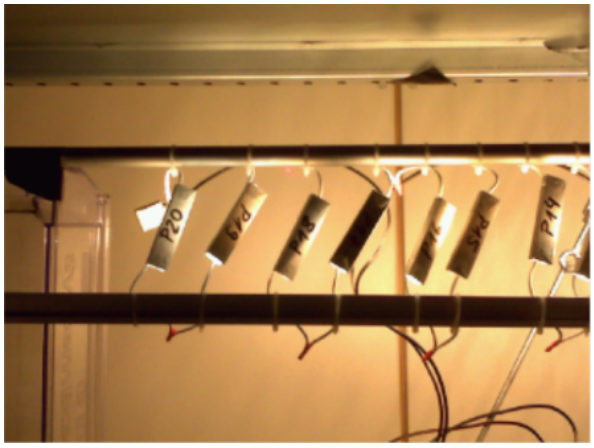

Figure 2: Operating the LED modules.

Results

As a result, there is a plausible value. The unpotted LED modules showed an aging behaviour as expected.

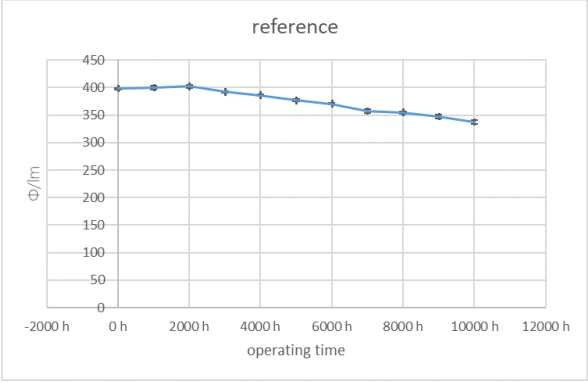

Figure 3: Decrease of luminous flux of unpotted modules.

The decrease in luminous flux to nearly 90% after 10'000 hours is expected by LM80- data of the individual LED. Also, the standard deviation is nearly constant over the entire experiment. The

colour coordinates of the LED modules were stable during the testing time.

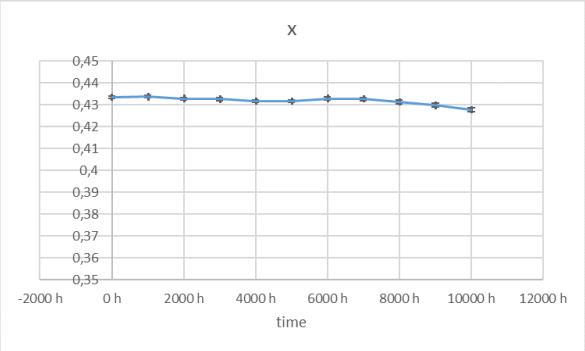

Figure 4: Colour coordinate *x* of the unpotted modules.

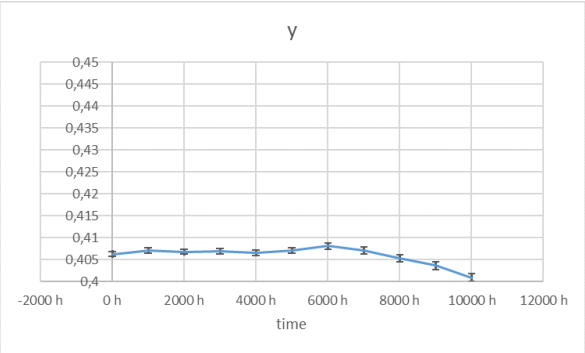

Figure 5: Colour coordinate *y* of the unpotted modules.

Material A

Using the first material — here called “A” — the drop in luminous flux after potting is shown in diagram below as the decrease from $t = -1000$ h to $t = 0$ h.

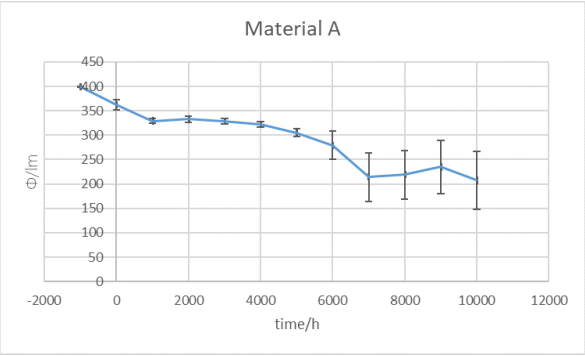

Figure 6: Luminous flux of the modules using material “A”.

During testing time luminous flux decreased to a value in the range of 65%. The standard deviation increased so that differences in luminous flux could be recognised also by the observers eyes.

During the first 1’000 hours the colour coordinates were shifting massively.

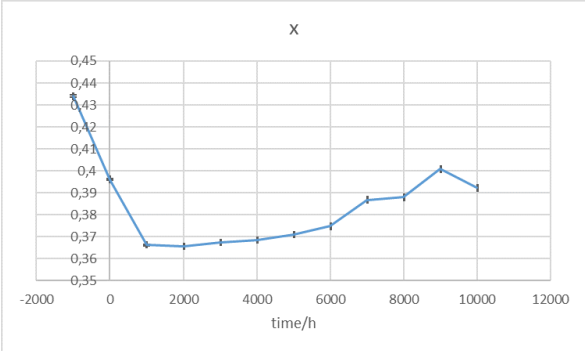

Figure 7: Colour coordinate *x* of the modules using material “A”.

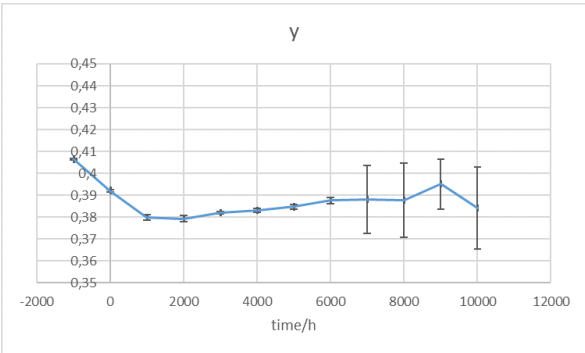

Figure 8: Colour coordinate *y* of the modules using material “A”.

Material B

Using the second material — here called “B” — the drop in luminous flux after potting is shown in diagram below as the decrease from $t = -1000$ h to $t = 0$ h.

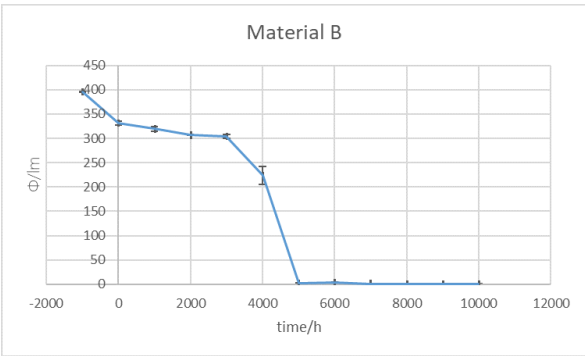

Figure 9: Luminous flux of the modules using material “B”.

After 3’000 hours the luminous flux dropped to a total fail.

During the first 3’000 hours the colour coordinates

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were stable. After total failing of the LED modules the colour coordinates give no more information.

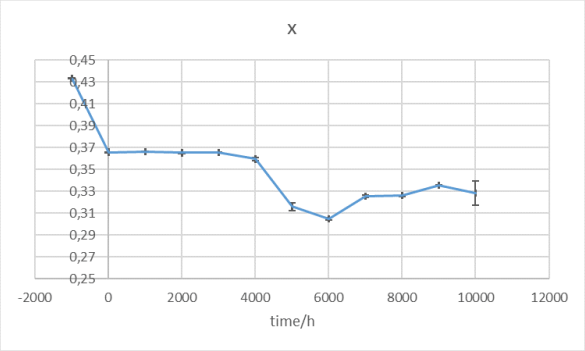

Figure 10: Colour coordinate *x* of the modules using material "B".

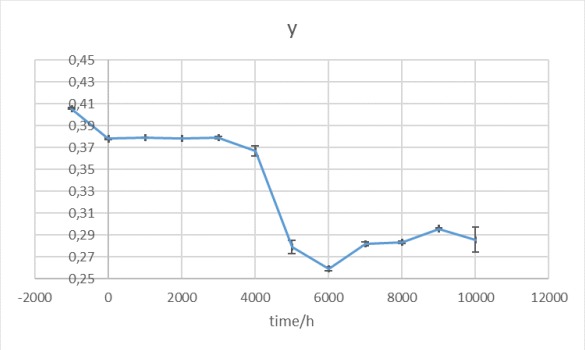

Figure 11: Colour coordinate *y* of the modules using material "B".

Material C

Material "C" showed a massive drop of luminous flux after potting the LED modules. The luminous flux recovered slightly within the first 1000 hours.

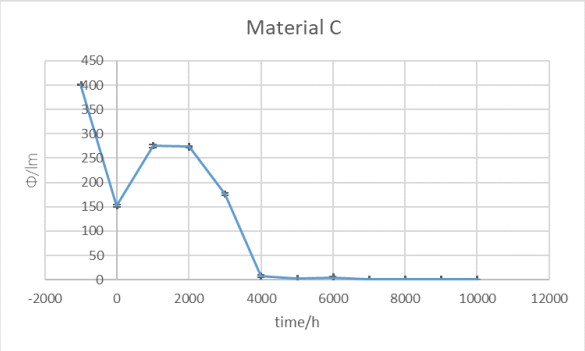

Figure 12: Luminous flux of the modules using material "C".

The total damaging started at 2'000 hours. After 4'000 hours there was no significant light output.

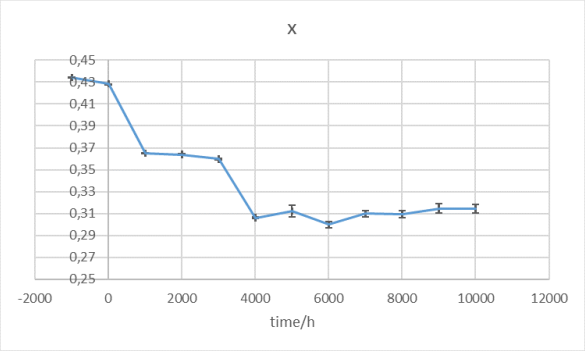

Figure 13: Colour coordinate *x* of the modules using material "C".

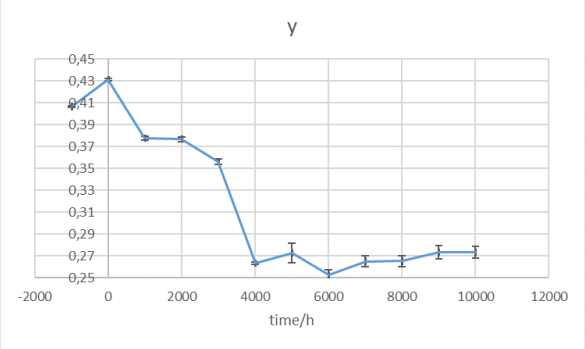

Figure 14: Colour coordinate *y* of the modules using material "C".

Material D

Material "D" showed the known drop of luminous flux after potting.

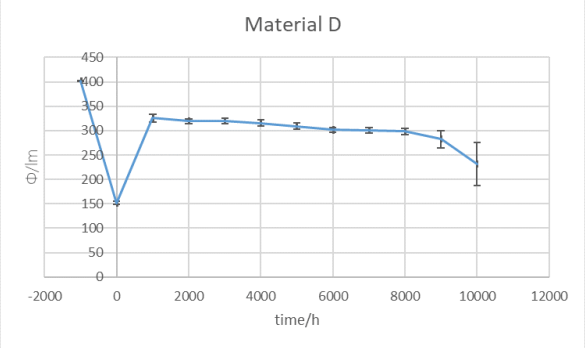

Figure 15: Luminous flux of the modules using material "D".

After recovering during the first 1'000 hours the luminous flux looked quite stable. After 8'000 hours the flux started to drop and the standard deviation increased. The probability of an impending catastrophic failure is high. Colour location changed during the first 1'000 hours and was then almost stable.

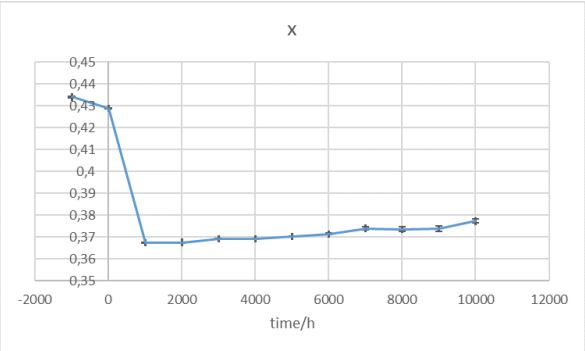

Figure 16: Colour coordinate *x* of the modules using material "D".

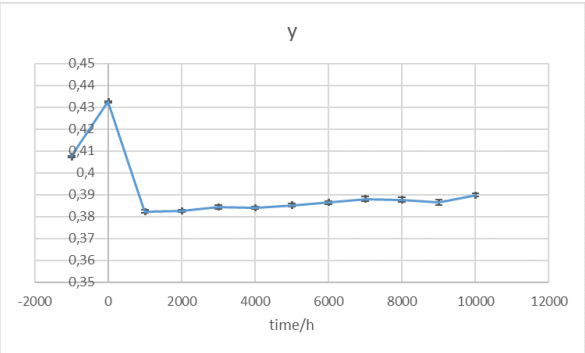

Figure 17: Colour coordinate *y* of the modules using material "D".

Material E

Material "E" showed a normal drop of luminous flux after potting the LED modules. After that the flux was almost stable for the entire measuring time.

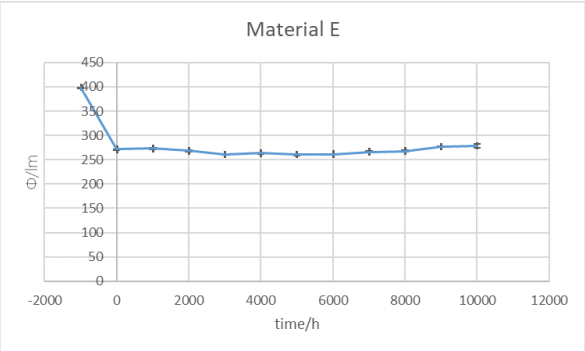

Figure 18: Luminous flux of the modules using material "E".

The colour location was almost stable until 8'000 hours. After that the colour shifted slightly to the yellowish region of the CIE1931 diagram.

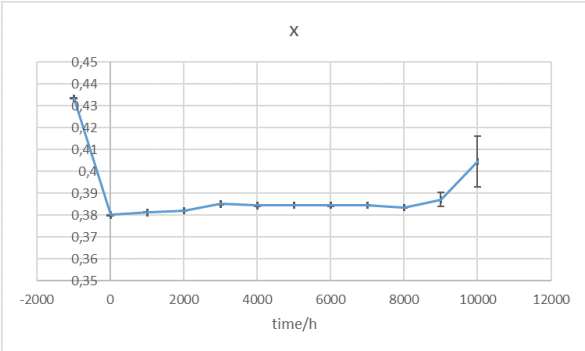

Figure 19: Colour coordinate *x* of the modules using material "E".

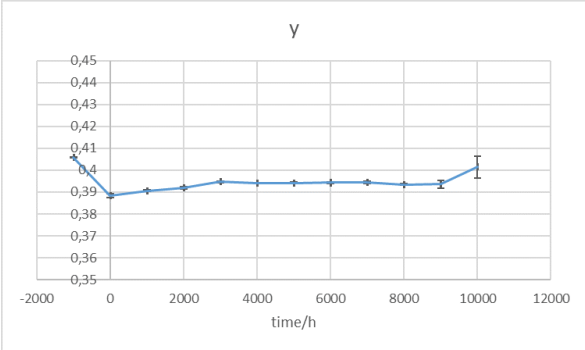

Figure 20: Colour coordinate *y* of the modules using material "E".

Discussion

Measurements show that there are totally different result. The results of materials "A", "B" and "C" show that these materials are not suitable for this application. Any further considerations on the lifetime can be omitted with these materials.

Material "D" seems to be an appropriate material for further investigation. When using the collected data from 5'000 hours to 10'000 hours, a curve fit to function

$$L = Be^{-\alpha t} \tag{1}$$

can be performed.

The least squares method is used. The calculated parameters are

$$B = 1,234917 \tag{2}$$

$$\alpha = 4,3 \cdot 10^{-5} \tag{3}$$

The extrapolation of the function leads to the following diagram.

With the calculated parameters it is possible to specify a lifetime L70B50.

$$t = \frac{1}{-\alpha} \ln\left(\frac{L}{B}\right) \tag{4}$$

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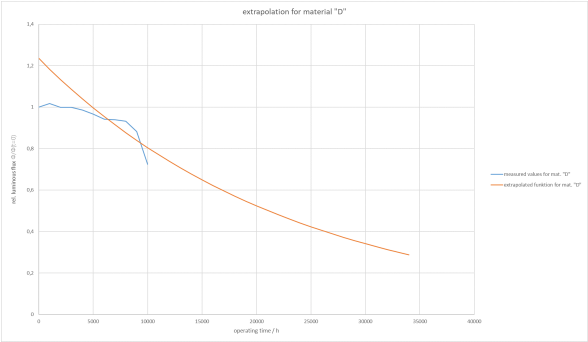


Figure 21: Extrapolation of flux for the modules using material “D”.

with (2) and (3) and

$$L = 0,7 \tag{5}$$

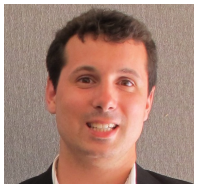
leads to

$$t = 13\,201\,\text{h} \tag{6}$$

This lifetime is significant lower than the usual lifetimes of unpotted LED modules, but the value seems plausible.

Also, material “E” seems to be an appropriate material for further investigation. Because of the very flat course of the measured flux values, it was not possible to get a curve fit to a falling function. Therefore, this sample continues to operate until there is a significant change or tendency.

Reliability of New Light Quality Metrics: Challenges and Opportunities



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Abstract

Together with high energy saving potentials, LED reliability is considered as one of the key advantages of this technology for artificial lighting. The developments of lighting applications and products bringing “more than illumination” in the lighting industry have highlighted the need for new metrics to qualify the light. As a result, reliability of these new metrics has to be evaluated in a similar way that luminous flux maintenance and chromaticity shifts have been in order to build accurate reliability models of luminaires. In this paper, the impact of spectrum aging on different light quality parameters will be presented (including TM30-15 and circadian parameters). Based on resent results, the influence of technologies on the maintenance of those parameters will be exposed highlighting the advantages and limits of the different technological approaches (e.g., multiple phosphors vs. n channels). In a third part, the challenges of modeling the light quality parameters maintenance over time will be discussed. Finally, recent results obtained using innovative modeling tools based on artificial intelligence and machine learning will be discussed underlining a solution to the modeling of light quality parameters maintenance.

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Introduction

Together with high energy saving potentials, LED reliability is considered as one of the key advantages of this technology for artificial lighting [1]. The promise of lighting systems with high reliability leads to long term cost saving linked to lower maintenance needs coupled with a reduction of the impact of lighting systems on the environment. In the past years, maturity of LED technologies has been growing. Based on past studies focusing on modeling the LED luminous flux maintenance [3] [4] [5], a list of known failure mechanisms associated to luminous flux drop as well as more accurate maintenance models have been developed [2]. Proposed models allowed to predict the flux behavior based on the LED environment (driving current, junction temperature, humidity, pollution) as well as abrupt failures of the LED component [1] [6]. Based on those results, LED luminous flux behavior for most of LED applications is well understood. However, the study of luminous flux as a failure mode must continue in order to cover more extreme applications and future technologies such as new phosphor upgrades (e.g., narrow band [8], quantum dots [9]) and material evolutions (EMC vs. PCT vs. PPA vs. recycled material [7]). With the growing knowledge regarding luminous flux as a failure mode and its associated failure mechanisms, new problematics and challenges have been raised in the lighting industry. In fact, chromaticity shift of lighting devices during their life is attracting more and more attention [10]. However, compared to luminous flux maintenance, limited information on related failure mechanisms and models have been published [11]. J. Lynn Davis et. al. [12] have recently published results to follow chromaticity shifts using scalar parameters $\Delta u'v'$ providing information on both the colorimetrical distance and direction of the color shift during lifetime.

For the past years, besides the initial function of providing light and maintaining its luminous flux and color point through time, additional functions have been developed regarding two main topics: Internet of Things (IoT) and Quality of Light. In a first hand, innovations related to IoT are including additional components to the luminaire such as sensors coupled with connectivity functions. This approach can be seen as a value generator as luminaires become able to collect and process data. From a reliability point of view, those new functions add complexity to the electrical system of the luminaire. As a result, the global reliability model of luminaires is increasing in complexity (including software reliability evaluation) [13]. In a second hand, light quality innovations are linked to new market requests regarding the characteristics of the emitted light. Light quality expectations can strongly vary from one field of application to another. Flexibility of LED colors and characteristics allows today to fit most of the niche requests regarding light specifications. Therefore, for these applications, the lighting system function is not only illumination but can also be composed of other requirements (e.g., a certain plant growth speed for horticulture lighting, a certain color saturation level for retail lighting). Reliability is defined as the ability of a component or system to fulfill its required functions in a certain environment for a specific period [1]. For those applications, reliability of the lighting systems can no longer be defined exclusively with a flux or a color maintenance but by the maintenance of other parameters depending on the full SPD reliability. The multitude of possible light quality criteria and associated metrics lead to an increasing complexity in failure modes. In fact, the entire lighting functions of the luminaire must be considered in reliability studies.

In this paper, the reliability of light quality metrics (LQM) will be discussed. In a first part, metrics from different applications will be presented highlighting the large variety of applications and associated metrics. In a second part, maintenance of light quality parameters resulting from spectrum variations of aged LEDs will be exposed. In a third part, the impact of technological and architectural choices on the reliability will be discussed. Finally, the first results of a new method used to predict SPD variations with stress using Artificial Intelligence (AI) and Machine Learning (ML) will be exposed.

Light quality

With the growing maturity of lighting technologies and controls, spectrum customization has become a new focus for the lighting industry. Innovative applications focusing on the effect of light beyond its conventional illumination function are emerging [14][15]. As a result, the quantity of LED based lighting solutions for horticulture, agriculture or wildlife care is constantly increasing [16][17]. In a wider scale, the impact of light on humans, including its impact on the circadian rhythms, is more and more considered and is foreseen as one of the major trends for indoor

lighting in the coming years [18][19][20][21]. Those “beyond lighting” applications require the implementation of new metrics (e.g Cs/CLA or EML for circadian lighting) which can be calculated using the spectral power distribution of the luminaire. Those light quality metrics (LQM) can be sorted into different categories.

Firstly, parameters characterizing the ability of the light to render the color of objects can be calculated from the SPD. To capture the impact of light source on human color perception the color rendering index (CRI — CIE Ra) developed initially by the International Commission on Illumination has been used for the past 50 years [22]. This parameter used a set of fourteen color samples which are used to characterize differences between the tested light source and a referent illuminant. However, with the development of solid state lighting, limitations of the CIE Ra have been exposed. As a result, the combination of conventional CIE Ra and its associated R9 value (rendering of the red color sample) has been increasingly requested to differentiate lights with an identical CIE Ra. Additionally, current market requests show a growing interest for expressing fidelity and saturation of colors with more precision and clarity. For that matter, researches have proposed new metrics for color rendering [23]. The proposal IES TM30-15 is based on a different approach to model color rendering. Firstly, it is based on 99 samples (compared to the fourteen used in the CRI calculation) allowing a better averaging of the global color rendering. Secondly, it uses a different color space (CAM02-USC) with no cut-off in the calculation of reference illuminant at 5000 K CCT between Planck and Daylight spectra [23]. In the IES TM30-15, three parameters are calculated from the light source SPD: a color fidelity parameter (Rf), a gamut parameter (Rg) as well as a chromaticity diagram depicting exposed saturation and hue shift for the different colors. Example of IES TM30-15 results are displayed on Figure 1 [24].

Secondly, some light quality metrics revolved around the positive impact of light on its target (humans, plants for horticulture, animals for agriculture). As an example, the impact of light on humans can be characterized through circadians metrics [26][27]. Circadian rhythm is the impact of natural light cycle on the hormones cycle of humans [29]. It has various effects on the human body such as triggering awakening and asleeping states, as well as energizing during the day. Its

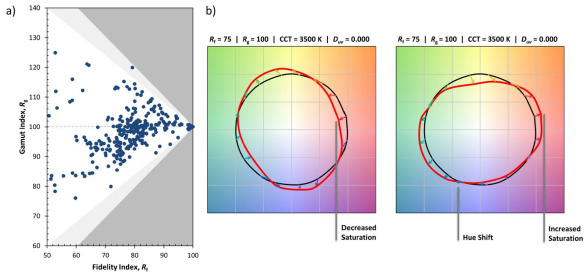

Figure 1: Example of fidelity index gammut index and chromaticity graph for TM30-15: two LEDs with same Rf and Rg can present different chromaticity diagrams [24].

impact on the mood is also important, it can help preventing depressions or softening Alzeimer symptoms [30]. Circadian rhythm has been proven to be affected by artificial lighting, the effects can be positive or negative depending on the light spectrum and intensity. Different metrics have been proposed to describe the impact of light on the circadian rhythm. MR (Melanopic Ratio) is the proportion of a light source present in the wavelength domain of melatonin (whose intensity peak is at 485 nm) [25]. Equivalent Melanopic Lux (EML) is equal to MR times the illuminance. Another parameter, Cs has been developed by the LRC (Lighting Research Center) at the RPI institute of New York state [26][27][28]. Cs is a more refined index based on extensive real case studies on pools of patients under different key environmental conditions. Cs results from equations translating the behavior of the different part of the eye stimulated by light. Those responses are used to calculate the CLA from which the Cs is derivate.

$$CL_A = \begin{cases} 1622\left[\int Mc_\lambda E_\lambda d\lambda + \left(a_{b\to y}\left(\int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda\right) - a_{rod}\left(1 - e^{-\frac{\int V'_\lambda E_\lambda d\lambda}{RodSat}}\right)\right)\right] \\ \quad \text{if } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda \geq 0 \quad \text{Condition 1} \\ 1622\int Mc_\lambda E_\lambda d\lambda \quad \text{if } \int \frac{S_\lambda}{mp_\lambda} E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda d\lambda < 0 \quad \text{Condition 2} \end{cases}$$

Macula S-Cone Visibility Rod suppression

Macula

Figure 2: CLA equation for circadian lighting [26][27][28].

Finally, some LQMs can be associated to negative impacts of light on the illuminated subject. In most cases associated metrics are linked to maximal proportions of identified wavelength(s) in the spectrum (e.g., wildlife care, telescopes). In other cases, such as conservation of food related products, protection of paint or fabrics, LQM can be evaluated through a “damage function” as shown in the next equation.

$$D = \sum Damage(\lambda) * P_{opt}(\lambda) \qquad (1)$$

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In the equation described above, the objective is to minimize the value of 'D'. Figure 3 summarize examples of applications requesting the implementations of LQMs, the associated "more than light" values and the related light quality metrics.

Application field	Light added value	Light quality metrics
Retail Lighting (Clothes / Food)	• Product protection (food / fabrics) • Product attractiveness through color rendering (accurate of saturated)	Damage function CRI / R9 TM30-15 Rf / Rg
Human centric lighting	• Well being • Improve sleep quality • Increase work productivity • ...	Cs EML
Wildelife care	• Animal well being and protection	Response curve
Horticulture lighting	• Increase plant growth rate and production	Response curve Photosynthetic Photon Flux Photosynthetic Photon Flux Density Phytochrome Photostationnary state

Figure 3: Examples of applications were the definition of new light quality metrics is requested.

As previously exposed, maintaining those "more than light" criteria during lifetime of the luminaire is a critical point for the products targeting the applications described in Figure 3. In addition of adding a new degree of freedom in the LED selection during product development, those metrics are becoming a new concern in design for reliability phases. In fact, as those LQMs are directly resulting from the spectrum they will be affected by the entire degradation of the system (light source, optics, luminaire body...). This paper focuses on the impact on the light source itself, but a final approach would have to consider the luminaire as a complete system. Starting from an LED point of view, all known failure mechanisms related to the different subparts of the component (die, light conversion, package) are affecting the SPD [2]. Those effects can vary from a distortion of the spectrum to changes in ratio of the different wavelength composing the SPD. In addition to the present complexity, the request for further parameters associated to the SPD can emerge from the market highlighting the importance of deeper researches regarding those parameters and their maintenance.

Results

Eighty High Power 2700 K 80 CRI LEDs from 2011 production have been aged following seven aging conditions (stress current / solder temperature). Evolution of electrical and optical parameters have been measured during stress. Luminous flux variations, color point shift and variations of some quality of light metrics (such as TM30-15 Rf) are extracted from measured SPDs and plotted for analysis. For clarity of graphical representation, only the aging data of the 0.7 A/mm^2, T_{solder}90 °C are displayed in this paper. Variations of luminous flux and color point are displayed in Figure 4 and Figure 5.

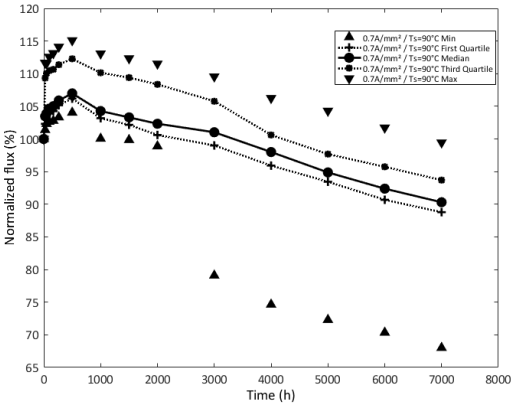

Figure 4: Flux variation for the 16 LEDs aged at 0.7 A/mm^2, T_{solder}90 °C.

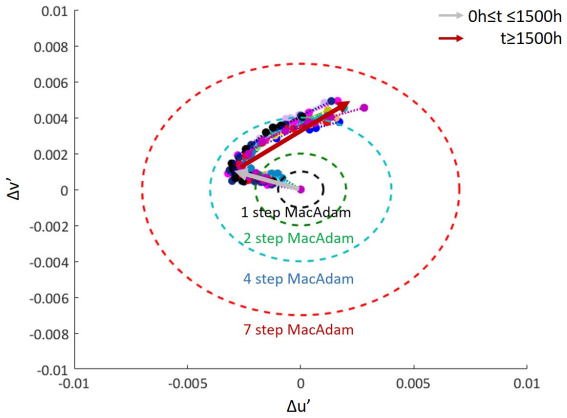

Figure 5: Chromaticity shifts in Δu' Δ'v' for the 16 LEDs aged at 0.7 A/mm^2, T_{solder}90 °C.

In most lighting applications, the failure criterion associated to lumen maintenance is the time in which half of the products have lost 30% of their initial flux (L70B50 [1]). The failure criterion associated to the chromaticity shifts is assumed to be achieved when a variation of more than five MacAdam steps is observed. For the aging conditions of samples presented in this paper, it can be observed that chromaticity failure is occurring much faster than luminous flux failure. As a result, for this LED archetype under those stress conditions, chromaticity shifts can be considered as the limited failure mode for conventional lighting applications. In order to identify the dominant failure mode for various applications, variations of multiple LQMs as a function of stress time have been plotted (Figure 6 and Figure 7).

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As it can be observed on Figure 6 and Figure 7, all parameters linked to quality of light are also decreasing with stress time. From Figure 5.a, the Cs parameter is decreasing with time as a result of the combination of lumen decrease and change in the spectrum aspect. Therefore, the circadian effect of this LED will decrease with time from a stimulation suitable for afternoon toward an evening suitable stimulation [29]. A decrease in color rendering capability of these LEDs is also observed both on fidelity and gamut. For certain lighting applications such a decay in color rendering cannot be accepted.

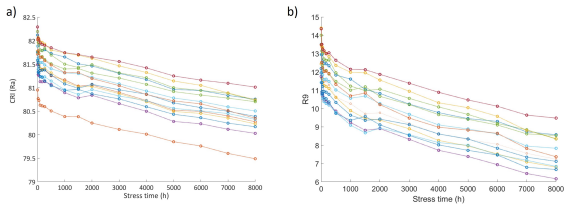

Figure 6: Color rendering indexes (Ra) (a) and R9 (b) variations for the 16 LEDs aged at 0.7 A/mm^2, T_{solder}90 °C.

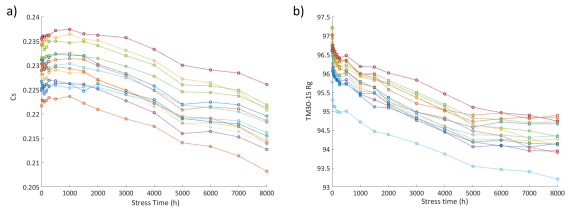

Figure 7: Cs index for circadian lighting applications (a) and TM30-15 Rg(b) variations for the 16 LEDs aged at 0.7 A/mm^2, T_{solder}90 °C.

Applying the data presented in Figure 4.b to a real case of food lighting (e.g meat) in which the R9 value must remain above a certain limit (from 0 to 10 to 80 depending on the applications) would disqualify these LEDs on the long term. In an application case in which the failure is defined as R9<10, it can be observed from the curves in Figure 2 to 5 that R9 is becoming the limiting failure mode of the lighting system using those LEDs. From that results, it can be exposed that the reliability of light quality metrics specific to a given application cannot be ignored as it can become the limited failure mode of the system (compared to luminous flux or chromaticity shift). As a result, developing lighting solutions able to cover new light quality specifications will only make sense as they can be maintaining throughout product life.

Discussion

Impact of LED module technology on LQMs reliability

As exposed in previous section, in a similar way to chromaticity shifts, variation in light quality metrics can be seen as a potential main failure mode and cannot be overlooked during development phases. These reliability limitations brought by the consideration of new lighting specifications can be different depending on the used technological approach. For regular lighting module using conventional white (blue and phosphors) LEDs, approach could consist on targeting initial light quality metrics specifications far above the defined minimal value to increase the luminaire lifetime. This pragmatic approach would have in most cases a negative impact on lm/W and would not guarantee that the maintenance of LQM will not remain the major failure mode. A second approach based on multi channels light module (composed on whites and single-color LEDs) could bring an innovative approach to the maintenance of LQMs. In fact, using this type of modules, adjustments of the final SPD could be conducted throughout the luminaire lifetime. Those adjustments can be based on an ageing model of the SPD for the different LEDs. Such model is today not developed, and its requirements will be discussed in this section. Another approach would be to use color points calibration and LQM at some key moments in the luminaire lifetime. Such a recalibration of the luminaire would significantly increase its lifetime which could then be solely defined by its luminous flux maintenance. This approach would also make possible the implementation after installation of new LQMs allowing for an upgradability of this luminaire. As a result, for applications in which the implementation and maintenance of light quality parameters is essential, a multi channel system with regular calibration would allow to substantially increase its lifetime and consequently considerably reduce long-term maintenance costs for such products.

Necessity of an SPD reliability model — opportunities brought by artificial intelligence and machine learning

As discussed, more and more lighting applications are requesting the implementation of

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new quality metrics to reflect their specifications and constraints. As a result, on a regular basis, new light quality metrics are emerging. This increases the need for a proper behavior modeling during the luminaire lifetime as these new LQMs can appear as the bottlenecking failure mode for the luminaire. As all those metrics are directly related to the light source SPD, modeling reliability of the entire SPD would significantly enhance flexibility in evaluating the reliability of present and future LQMs. However, modeling of the full SPD during time requires a flexible enough model to cover all known and unknown failure mechanisms for present and future technologies. It should be able to to cover shifts and distortion of SPDs with stress. Phenomenological models have been proposed in previous papers [29] which allow to capture a full conventional white spectrum with a limited set of parameters. These models allow to fit most of spectrum variations linked to known failure mechanisms (shifts, distortions and changes in wavelengths ratio). For multi-channel lighting systems, a sum of phenomenological models can be used to model the entire resulting spectrum. However, new models will have to be proposed to consider new technological innovations (e.g., narrow band phosphors, quantum dots-based LEDs, three phosphors-based LEDs) in order to be able to generate a consistent reliability modeling of the present and future lighting systems. Even with a proper SPD modeling method, it is still challenging to include all stress factors affecting the SPD and to cover all present and new technologies. An innovative approach would be to use artificial intelligence combined with machine learning to develop a solution [31][32][33]. Artificial intelligence and machine learning have been used in the past years to solve numerous complexe problems, from cryptology to optimization of complicated industrial processes. Using a neural network and a proper training data set, this innovative mathematical tool would allow to predict variations of SPD based on input encountered stress and lighting system architecture inputs as exposed in Figure 8.

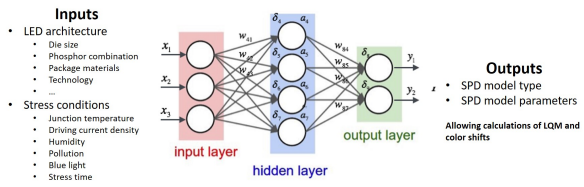

Figure 8: Example of a possible neural network used to predict SPD reliability using AI and ML.

Current challenge of this AI based approach is the required quality and size of the training dataset. In order to obtain sufficient precision in the spectrum prediction, a large set of aged spectra for various technologies and ageing conditions has to be collected. So far, precision obtained with the thousand spectra measured in the present experiment was not satisfactory. The key challenge is SPD aging data is not something that can be obtained in current reliability reports as the luminous flux and color point can be (on LM80 reports for example). To succeed in the elaboration of a global SPD reliability model, an effort in LED/Lighting industry would have to be conducted in order to collect spectra resulting from reliability tests on LEDs or luminaire field returns. Three main outcomes are expected: the ability to predict SPD model parameters, the ability to predict LM-80 tests based on small deviations of an existing LED (similarity rules), and a validation of the “AI as a solver” method for the lighting industry using Pi Lighting technology.

Conclusions

In this paper, the recent importance of light quality in the lighting industry through “more than light” effects has been exposed highlighting a large panel of potential applications. The definition of light quality as well as the associated metrics have been proven to be application dependent. Current aging data have demonstrated a strong impact on reliability of light quality metrics (together with chromaticity and luminous flux maintenances). These criteria can therefore appear as the first real, user dependent limiting failure modes. Importance of light module architecture to cover these particular lighting applications has been discussed. Light modules using multi-channel systems associated with a regular calibration approach show a potential to strongly maintain both color point and light quality metrics within specifications during the luminaire lifetime. Finally, the large potential of using artificial intelligence and machine learning to build up an SPD reliability model (covering the maintenance of all LQM) has been exposed. This approach would require a joint collaboration within the lighting industry in order to collect enough SPDs resulting from various LED architectures and reliability test data to build a robust data training set to train properly our neural network.

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Acknowledgment

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References

[1] W.D. van Driel, X.J. Fan, Solid State Lighting Reliability: Components to Systems, ISBN 978-1-4614-3066-7, 31 August 2012, Springer, 617 pages.

[2] M. H. Chang, D. Das, P. V. Varde and M. Pecht, Light-emitting Diodes Reliability Review, Microelectronics Reliability, vol. 52, no. 5, pp. 762–782, May 2012.

[3] N. Narendran, J. D. Bullough, N. Maliyagoda, and A. Bierman, "What is Useful Life for White Light LEDs?," Journal of the Illumination Engineering Society, vol. 30, no. 1, pp. 57–68, Jan. 2001.

[4] `http://www.ies.org/.`, TM21 — LM80

[5] Hao Jian et al., The establishement of reliability model for LED lamps, Journal of Semiconductors, Volume 37, Number 7

[6] W.D. van Driel, X.J. Fan, Solid State Lighting Reliability: Components to Systems Part2, ISBN 978-3-319-58174-3, 2017, Springer, 700 pages.

[7] Ledinside.com, Asia Manufacturers EMC lead frame strategy (2013)

[8] Phillipp Pust et al., Narrow-band red-emitting Sr[LiAl3N4]:Eu2+ as a next-generation LED-phosphor material, Nature Materials, vol 13, 2014, 891–896

[9] Yashuiro Shirasaki et al., Emergence of colloidal quantum-dot light-emitting technologies, Nature Photonics vol 7, 13–23 (2013)

[10] Guangjun Lu et al., LED based Luminaire Color Shift Acceleration and Prediction, Solid State Lighting Reliability: Components to Systems Part2, Chapter 9, ISBN 978-3-319-58174-3, 2017, Springer

[11] J. Lynn Davis et al., Chromaticity maintenance in LED devices, Solid State Lighting Reliability: Components to Systems Part2, Chapter 10, ISBN 978-3-319-58174-3, 2017, Springer

[12] J. Lynn Davis et al., Understanding chromaticity shifts in LED devices through analytical models, Microelectronics Reliability 84 (2018) 149–156

[13] D. Schenkelaars et al., The Next Frontier: Reliability of Complex Systems, Solid State Lighting Reliability: Components to Systems Part2, Chapter 22, ISBN 978-3-319-58174-3, 2017, Springer

[14] Sun-Ja Kim et al., Effects of LEDs on net photosynthetic rate, growth and leaf stomata of chrysanthemum plantlets in vitro, Scientia Horticulturae vol 101, 143–151 (2004)

[15] Gioia D. Massa et al. Plant productivity in response to LED lighting, HortiScience, vol 43, 1951–1956 (2008)

[16] Klaus T. Martin et al., Solid State light simulator for horticultural applications, Power electronics conference (2017)

[17] Alicia M. Dimovski et al., Artificial light pollution: Shifting spectral wavelengths to mitigate physiological and health consequences in a nocturnal marsupial mammal, JEZ-A (2018)

[18] Sen, S., Flyvholm, A., Xylakis, E., Nielsen, S. M. L., Hansen, E. K., Mullins, M. F., Triantafyllidis, G. (2017).Towards assessing the impact of circadian lighting in elderly housing from a holistic perspective. In ARCH 17: 3rd international conference on architecture, research, care and health. Conference Proceedings (1 ed., pp.227–240). Polyteknisk Boghandel og Forlag

[19] A. Borisuit et al. Effects of realistic office daylighting and electric lighting conditions on visual comfort, alertness and mood, Lighting Research Technology, vol 47, issue 2 (2015)

[20] MG Figueiro et al., Circadian-effective light and its impact on alertness in office workers, Lighting Research Technology (2018)

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[21] MG Figueiro et al., Office lighting and personal light exposures in two seasons: Impact on sleep and mood, Lighting Research Technology, vol 48, issue 3 (2016)
[22] http://www.cie.co.at/
[23] IES TM-30-15 IES Method for Evaluating Light Source Color Rendition, standard by Illuminating Engineering Society, 2015, ISBN(s): 9780879953126.
[24] U.S. Departement of Energy, Solid State Lighting Technology fact sheet, Evaluating color rendition using TM-30-15
[25] Circadian Lighting Factsheet, DELOS.
[26] M. S. Rea et al. “Circadian light, review”, Journal of Circadian Rhythms 2010, 8:2, http://www.jcircadianrhythms.com/content/8/1/2.
[27] M. S. Rea et al. “Modeling the spectral sensitivity of the human circadian system”, Lighting Research and Technology published online DOI: 10.1177/1477153511430474 Lighting Res. Technol. 2011; 0: pp1–12, 14 December 2011.
[28] M.S. Rea et al., “Modeling the spectral sensitivity of the human circadian system- Corrigendum”, Lighting Research and Technology 2012; 44(4): 386–396. DOI: 10.1177/1477153511430474 Lighting Res. Technol. 2012; 44: 516 s
[29] T. Mérelle and B. Bataillou, A methodology to assess the impact of LED process variability in colorimetry, LED professional Syposium 2017
[30] MG Figueiro et al., Research Note: A self-luminous light table for persons with Alzheimer’s disease, Lighting Res. Technol.; vol48: 253–259 (2016)
[31] Zoubin Ghahramani, Probabilistic machine learning and artificial intelligence, Nature 521, 452–459 (2015)
[32] Yann LeCun et al., Deep Learning, Nature 521, 436–444 (2015)
[33] Michael Nielsen, Neural Networks and Deep Learning

Destroy in the Lab to Last in the Field – LED Robustness, Reliability and Life Time Testing

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Abstract

The LM-80 and TM-21 method is providing a basic information about LED lifetime. But there are also challenges and problems which should be addressed in order to read and use the resulting data in a professional way. The new IEC 63013 standard provides additional methods to extrapolate the lifetime based on LM-80 data. True lifetime modeling is only possible with extensive robustness testing in order to derive the different failure mechanisms and the respective failure rates.

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The basics of LM-80 and TM-21

A well-known method for lifetime evaluation of LED is LM-80 and TM-21. It was the first internationally accepted standard to perform lifetime tests and predictions and several certifications like Energy Star or DLC are requesting the LM-80 reports. Sometimes the difference between the LM-80 and the TM-21 is not always clear to the user and this may lead to challenges in the communication and understanding.

LM-80 is describing a measurement procedure to generate lifetime test data of LED within certain standardized boundary conditions. It requests that the LED are tested and stressed at 2 different temperatures minimum and defines other requirements like the temperature tolerance on the LED package during the stress test. The testing of the LED has to be performed for at least 6000 h. It does not give any information on the lifetime prediction and the LM-80 test can also not be failed. It is just a definition how to generate and collect the test data.

TM-21 is describing a calculation method to estimate a lumen maintenance lifetime extrapolation based on the values and results generated in a LM-80 test. It is based on a standard exponential decay function and allows an adjustment of the lumen maintenance and gives the respective lifetime estimation. The reported lifetime is restricted to 6 times of the actual measurement hours of the LM-80 test. This means a LM-80 test with 6 kh can only cover lifetime estimations based on TM-21 of up to 36 kh.

With the raising demand on LED lifetime and quality, requests like predictions of the color shift and methods for interpolations between test currents are raising. These requests are more difficult to answer than one would expect because there are already significant limitations of the existing methodology and further developments may need new approaches.

Limitations of the LM-80 and TM-21 method

The LM-80 and TM-21 method provides a first indication which is supported by freely available software to perform the calculation. However the basic model can lead to strange effects which, if not used and interpreted properly, could lead to misleading results and difficulties in discussions.

Example 1: Upward projection and infinite lifetime

This example shows real LM-80 data and its TM-21 lifetime extrapolations. For the 85 °C and 105 °C testing conditions, the curves would predict or estimate a positive aging where the LED will get brighter over time.

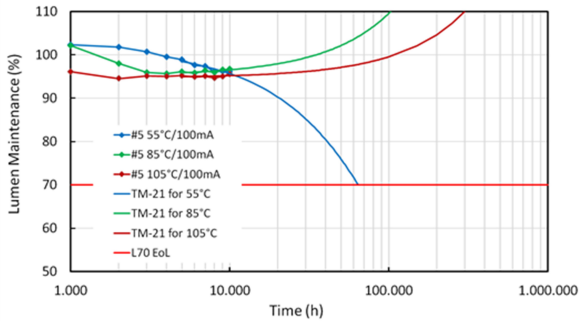

Figure 1: LM-80 data with increasing luminous flux prediction.

This is not possible and the TM-21 is also setting boundary conditions for this case e.g., that the reported lifetime is only 6 times the testing time even if a positive aging would be the result of the TM-21 calculation. However the calculated lifetime is mentioned in the report and if not properly addressed the value may be still used for comparison.

Example 2: Arrhenius violation by crossing of projected curves

This example shows real LM-80 data with its TM-21 lifetime extrapolations. In this case the operation of the LED under higher temperatures (Ts = 105 °C) would lead to a significant longer lifetime compared to the lower operation temperatures.

This is also not possible and could lead to difficulties in the communication and interpretation of the extrapolation results. Usually the LED which sees the higher temperature is also aging faster.

These two examples show some of the limitations of the LM-80 and TM-21 method. In general the method can be considered as a conservative

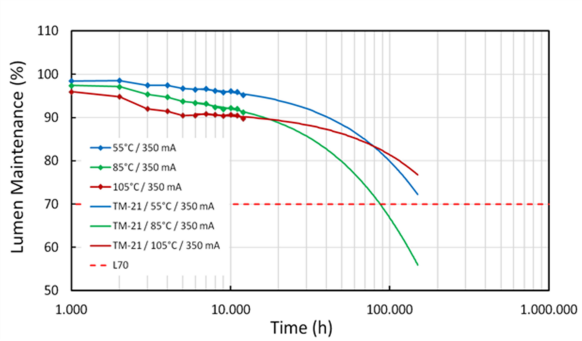

Figure 2: LM-80 data with crossing curves.

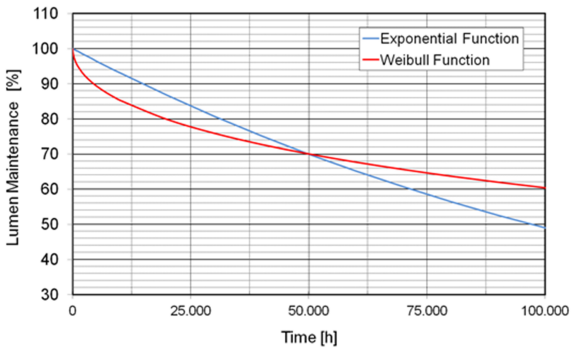

Figure 4: Different fit functions.

estimation. The method is applying a simple exponential function without any evaluation if the data and the LED setup supports such a simplification.

In the initial discussion around LM-80 and lifetime projection there have been also other functions which may be more suitable to the aging behavior of LEDs. Up to now the community could only agree to the exponential function. The following picture shows the fit quality of real LM-80 data with an exponential fit and a Weibull fit. The Weibull function matches the behavior much better.

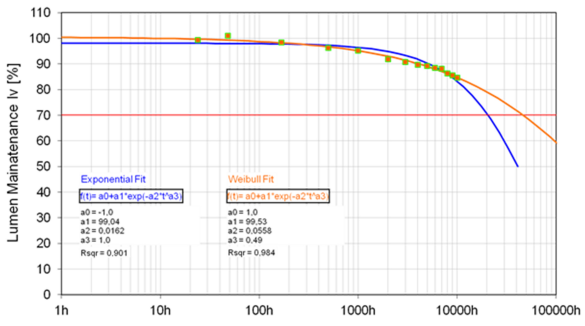

Figure 3: Exponential Fit vs Weibull Fit.

The choice of the fit function has a big impact on the resulting lifetime extrapolation. The exponential function interprets a strong initial degradation significantly different than the Weibull function.

The graph shows a L70B50 lifetime of 50 kh but the shape of the curves are completely different. We will later see the typical aging mechanisms for LED which suggest to follow the Weibull function as a more adequate fit.

Beside the choice of the functions there are additional drawbacks of the TM-21. The extrapolation is performed for each temperature independently and the information which could be used by combining the data at the different temperatures is not used. In addition the TM-21 method is sensitive to small variations of the measurements from the LM-80 test. Considering the measurement tolerances of integrating spheres which are often used to determine the luminous flux of the LEDs the accuracy of the extrapolation has to be evaluated carefully and extremely long lifetimes should be proven in additional test.

Proposals of additional lifetime assessments

An improvement or extension of the LM-80 and TM-21 method is under discussion for a long time and the IEC 63013 standard is already providing additional proposals to perform a long term luminous flux maintenance projection using additional and different methods. These methods can be considered if the results of the LM-80 and TM-21 does not lead to reasonable conclusions.

The IEC 63013 addresses the issue with the flat or upward projection by introducing the border function method. The border function method is also using the exponential model as a conservative estimation of the actual long term luminous flux maintenance. Instead of a lifetime prediction it gives a kind of threshold for different Lxx lifetimes.

If the test data of the last 2000 h and at least 3 successive measurement points is higher than the threshold given by the border function and the slope of the last 2000 h test data is more flat than the corresponding values of the border function the target value of the border function can be used as projected median life of the LED.

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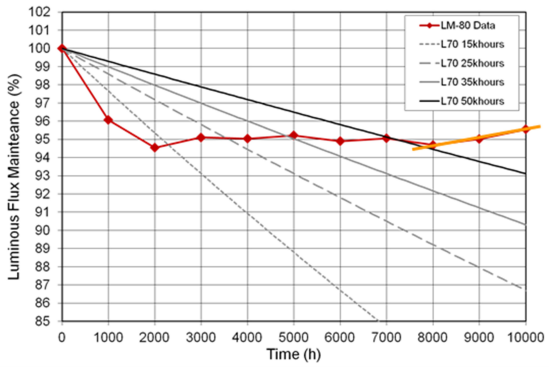

Figure 5: IEC 63013 Border Function Example.

The IEC 63013 also states another important annex: The method of temperature acceleration — Arrhenius method. This method is based on the assumption that a higher temperature is accelerating the aging of the LED. Therefore the degradation results can be scaled based on the shape of the aging curve at highest temperatures. Here the LM-80 data can be used and it is recommended to have 3 temperatures with at least one higher than 85 °C to achieve a higher acceleration. A further boundary condition is that the curves are not crossing between the different temperatures. The following data set is used to explain the example of temperature acceleration according to Arrhenius.

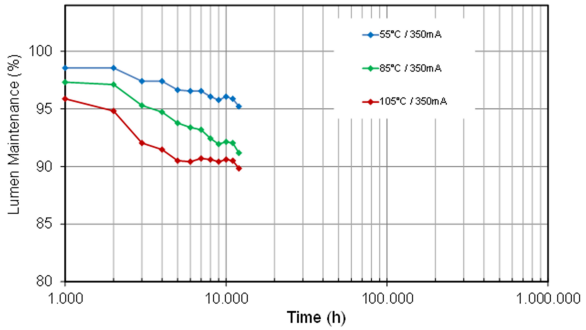

Figure 6: LM-80 test data for different temperatures.

The graph shows real test data of an LED under LM80 conditions. The curves do not cross and the aging is faster with higher temperature. In order to determine the acceleration factor the activation energy for the given aging mechanism has to be determined.

Use the last data point from the lowest temperature (in this case the 12 kh at 55 °C) and draw a horizontal line through this last data point. Determine the crossing points to the other temperatures and derive the respective time.

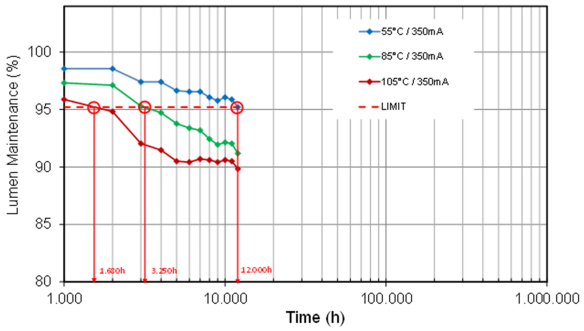

Figure 7: Deriving the lifetime for the higher temperatures based on the limit of the lowest temperature data.

With this data the activation energy EA can be calculated by plotting the data points for all three temperatures in a Ln(t) vs 1/T diagram.

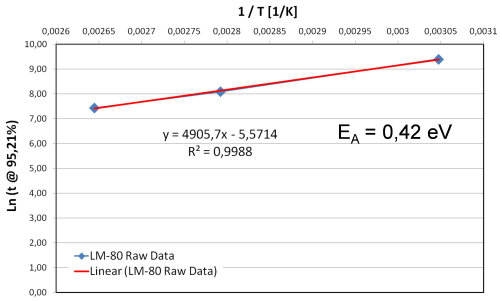

Figure 8: Deriving the activation energy EA.

Fitting a linear function through the data points will give a characteristic slope which has to be multiplied by the Boltzmann constant in order to calculate the activation energy EA (eV). The detailed formula can be found in the IEC 63013.

By applying the acceleration factor from 105 °C to 55 °C to the test data of 55 °C one can predict the further aging of the LED.

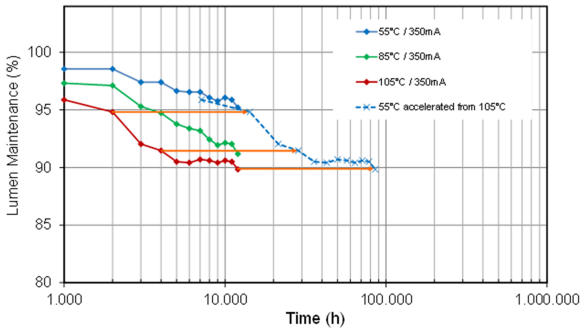

Figure 9: Applying the acceleration factor to the 55 °C measurement data.

Beyond the official standard one could even think

of a combination of the acceleration method and the border function. The following graph shows the acceleration of the 85 °C data based on the 105 °C data and the resulting degradation. One can also derive the crossing point of the L70B50 border function of the accelerated data already after 6000 h.

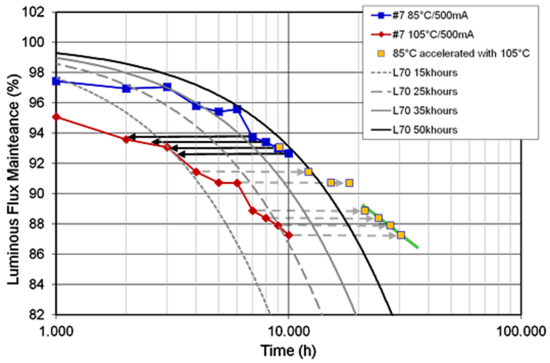

Figure 10: Example of the border function in combination with the acceleration method.

The purpose of acceleration is to save time and prove that the aging does not show a sudden drop in the luminous flux. A test under harsh conditions and a visible degradation is often more useful than a moderate operation and a flat and constant luminous flux maintenance.

Why destructive robustness testing helps to solve these issues

In order to provide “good” LM-80 and TM-21 values the LEDs are often operated under moderate operation conditions with low temperatures and driving currents. This leads to very little degradation in the luminous flux which translates to a long extrapolated and estimated TM-21 lifetime.

From such a moderate operation condition it is not possible to evaluate the real behavior of the LED over the complete lifetime. The following picture shows typical aging and degradation mechanisms of LED.

After an initial degradation which is mainly chip related there is a first period of predominant package aging, followed by a stabilization phase and finally a long term chip degradation. A soft operation will not disclose the different mechanisms and a proper lifetime modelling is also not possible.

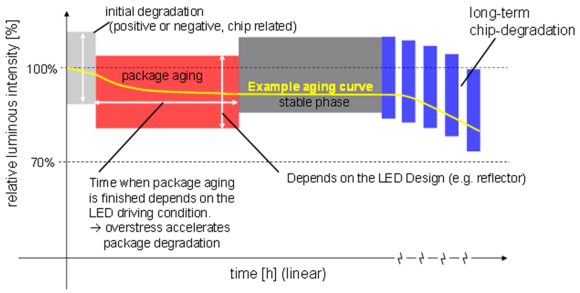

Figure 11: Typical aging phases of LED.

OSRAM Opto Semiconductors is therefore using a different approach to determine the behavior and lifetime of LEDs over the complete lifetime. This involves testing of the LED until failure. It is important to understand when and under which conditions the LED will age and finally fail in order to estimate the safe operation under moderate operation conditions. This philosophy is called robustness testing.

We operate the LED intentionally significantly outside the application conditions and the maximum ratings stated in the data sheet. The picture below illustrates the failure risk level for two different stress conditions (e.g., operation temperature and driving current).

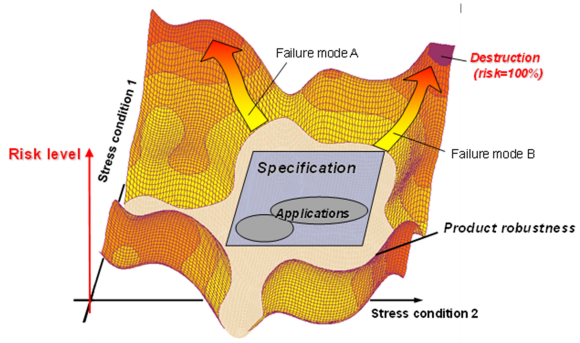

Figure 12: Illustration of different stress conditions for robustness testing.

If the stress conditions get very high the risk of a failure and aging also rises until the LED is destroyed or fails. Of course it is very important not to cause additional failure mechanisms. Therefore the conditions have to be chosen carefully based on a lot of experience and understanding of the LED, the construction and the failure modes.

This accelerated aging of the LED gives valuable information about the failure mechanisms (e.g., lens cracks, converter cracks, package browning), the aging of different components of the LED

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(e.g., chip, package and converter) as well as the shape of the luminous flux degradation.

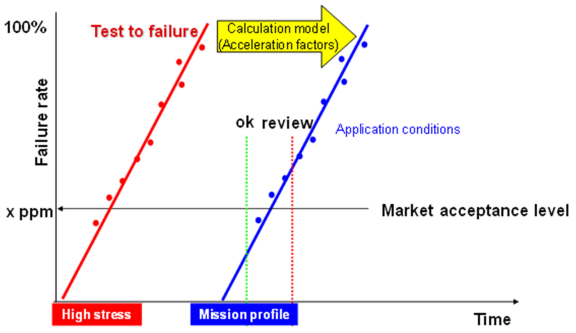

Figure 13: Transfer of the failure rates under high stress conditions to typical application conditions.

Based on the knowledge of the failure mode, failure rates, and stress conditions we can calculate the degradation levels under application conditions and the resulting failure rates. These data sets allow also the creation of lifetime models.

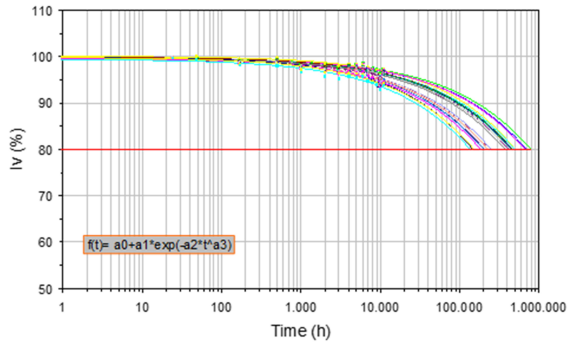

Figure 14: Examples of lifetime data with lifetime modeling.

The lifetime models are fit to the different application conditions using the proper fit function which models the degradation behavior of the different aging mechanisms of the LED best.

The LM-80 and TM-21 method can only provide a medial life projection which is indicated by the B50 value. A serious answer to other Bxx values is not possible due to the small sample size of LED used in the LM80 test.

Using the big amount of LED data from different robustness test under different conditions gives a much higher statistical sample size and allows also an extrapolation of different Bxx values. Therefore OSRAM Opto Semiconductors is able to provide LM-80 and TM-21 data and in addition lifetime extrapolation LxxByy based on expert knowledge and internal robustness tests to

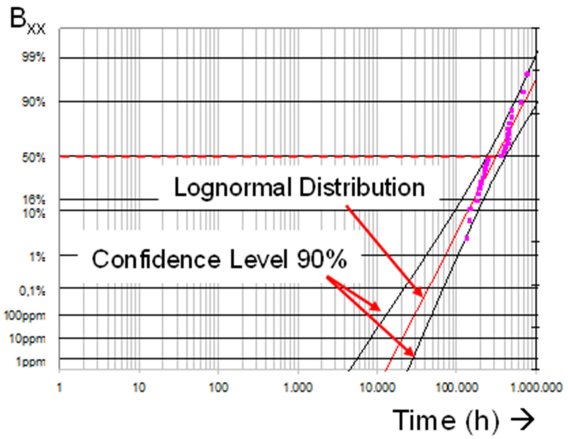

Figure 15: Examples of distribution data with lifetime modeling.

ensure that the LED fits perfectly to the given application conditions.

Conclusions

LM-80 and TM-21 data provide a first impression on lifetime of LED but are not able to model and predict the real behavior properly because the used conditions are not hard enough. Additional methods like the border function and the Arrhenius method can be used to evaluate the lifetime projections and provide more reasonable answers. A detailed lifetime modelling requires extensive knowledge on the aging mechanisms and failure rates which can only be derived from wide-ranging robustness tests.

Temperature Profiling of Secondary LED Optics by Infrared Thermography

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Abstract

Over the last few years, the power density of white LEDs has increased dramatically. Whilst there are large efforts to optimize the thermal management and thus the temperature stability of the LEDs, less attention is paid to the temperature of the secondary optic. If the secondary (polymer-) optic is permanently operated at high temperatures, its optical properties or even its geometry might change. Therefore, it is important to have an exact knowledge on the temperature profile within the secondary optic.

Here, the temperature profile of a secondary polymer optic is analysed in combination with a high-power LED module by infrared thermography. Two different materials for the secondary optic are investigated: polymethyl methacrylate (PMMA) and polycarbonate (PC). In the experiments, the temperature of the LED module is set to 85 °C with an external temperature controller. To examine the temperature profile within the optic, a cross-sectional cut is prepared and the surface is polished to optical quality. The investigation yields the exact temperature profile within the optic. In particular, the temperature at the inner surface is determined precisely.

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Introduction

As power dissipation and thermal robustness of LEDs rise, their power density and temperature, in particular the phosphor temperature, increases as well. While modern LEDs are designed to withstand high temperatures, it has to be made sure that their application environment also keeps up with this trend. A higher temperature stability of the LED and the primary optic might result in conditions, where the temperature of the secondary optic exceeds its specified working temperature range. This is of particular interest if the secondary optic is made out of a polymer. The heat distortion temperature (HDT) of the commonly-used materials for secondary optics, such as polymethyl methacrylate (PMMA) and polycarbonate (PC) is at 95 °C [1] and 122 °C [2], respectively (both values according to ISO 75 at 1.8 MPa). If the secondary optic is permanently operated above these temperatures, its optical properties might degrade [3]. In a worst case scenario, even a deformation is possible. While glass optics are certainly an alternative, polymer optics are preferred by lighting manufacturers due to their lower cost and weight. An exact knowledge on the temperature profile within the secondary optic is thus crucial for high-power LED applications.

Experimental Details

The temperature profile of two secondary optics made of PMMA and PC in combination with a high-power LED module are investigated. Both optics have identical geometry and differ only in material. Figure 1 shows a scheme of the used LED module and the geometry of the optic. The LED module consists of four high-power LEDs on a printed circuit board (PCB) with an aluminum core (Figure 1, top part). The LEDs are connected in series and arranged in a square 2×2 array.

In Figure 1, the secondary optic is shaded in blue. For some experiments, a cross-sectional cut is performed along the symmetry axis of the optic. This allows to measure the temperature profile within the optic (Figure 1, bottom part). In this case, two of the LEDs are fully covered, while the other two are only half covered by the optic. The whole setup is mounted on a sample holder, which is equipped with a heater and a temperature controller. To control the operation current of the LEDs and to measure the electrical

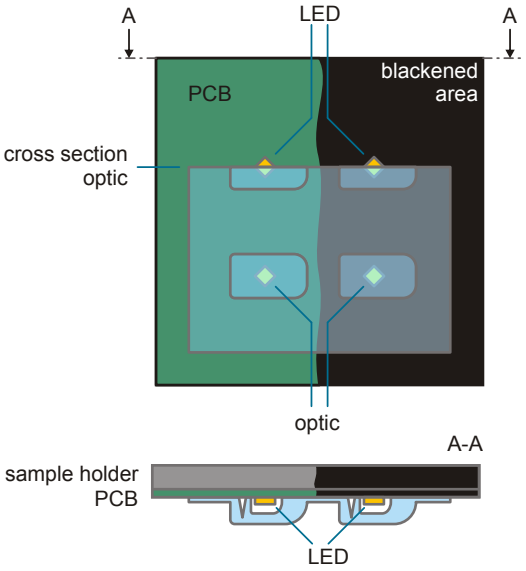

Figure 1: Schematic drawing of the setup. The LED module and the secondary optic are mounted on a sample holder with external heating. One half of the PCB is painted in black to enhance the emissivity. For some experiments, the optic is cut open to reveal the cross section (top). For temperature profiling of the secondary optic, the module is operated upside down (bottom).

power consumption a source measure unit (Tektronix Keithley 2600) is used.

Transmittance measurements in the visible spectral range are carried out using a UV-Vis-NIR spectrophotometer (Agilent Technologies Cary 5000). The LED emission spectrum is recorded with an absolute photoluminescence quantum yield measurement system (Hamamatsu C9920-02G).

Measurements of the temperature distributions in operation are performed with an infrared (IR) thermography camera (InfraTec ImageIR 8380S), which uses an indium antimonide (InSb) focal plane array (FPA) snapshot detector with a geometric resolution of 640 × 512 px. The spectral range for detection is between 2.0 µm and 5.7 µm.

In principle, infrared thermography allows a precise measurement of the radiation intensity only. However, if the emissivity value for the surface of the investigated material is known, the exact temperature can be deduced. Parts of the LED module are thus painted in black. This ensures for the painted areas in very good approximation a homogeneous black-body emissivity of $\epsilon \approx 1.0$.

It is obvious that the approach of a painted

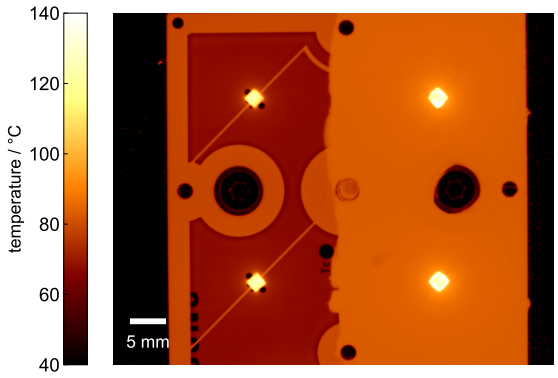

Figure 2: Thermographic image of the LED module without secondary optic. The right half of the board is painted in black.

reference point is not reasonable to determine the temperature of the polymer optic. The painted part of the optic would lead to an additional temperature increase, since the visible part of the LED emission would be absorbed by the black paint resulting in false temperature values. Thus, the emissivity values of both polymers are estimated as follows: First, the transmission and reflection spectra are recorded in the near-infrared spectral range with a Fourier transform infrared spectrometer (Bruker Vertex 70 with a combined transmission and specular reflection unit A510/Q-T). On the basis of these data, the spectral absorbance is calculated, weighted with the black body spectrum, and then integrated for the sensitivity range of the thermography camera, i.e., in the spectral range from 2.0 µm to 5.7 µm. Finally, the integrated absorbance is compared to the integrated emission intensity of a black body in the same spectral range; the ratio of these values approximates the emissivity of the sample. For PMMA as well as PC an emissivity value of $\epsilon = 0.95$ is found.

The thermographic images shown in this work are all corrected for the emissivity of the material. To mimic the operation in a warm environment, the sample holder is kept at a constant temperature of 85 °C. This is the maximum reference temperature for the LED system. The current of the LED module is set to 1050 mA, the voltage amounts to 12.5 V. This leads to an electrical power consumption of about 13 W for the total LED array. Prior to the thermographic measurements, the module is run for two hours to reach thermal equilibrium.

Experimental Results

Thermographic imaging of the LED module

Figure 2 shows a thermographic image of the LED module without secondary optic. In this image, the blackened part of the PCB (compare Figure 1) is seemingly warmer than the other. This is due to the larger emissivity ($\epsilon \approx 1.0$) of this area compared to the unpainted one. In fact, the entire PCB is at the same temperature of 85 °C. As proven in preceding investigations, the LED itself has an emissivity of $\epsilon \approx 1.0$. In this experiment, the surface temperature of the LEDs reaches an average value of 125 °C.

Optical properties of PMMA and PC

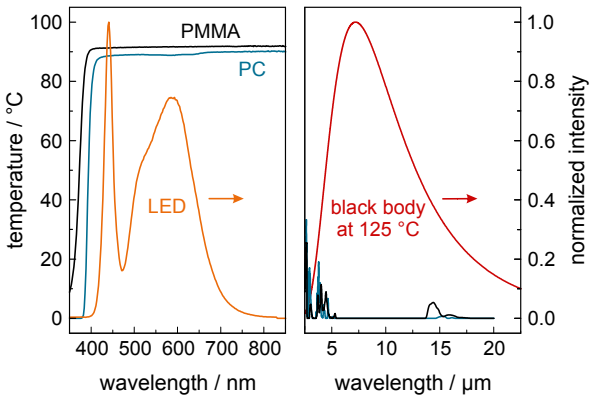

Figure 3: Transmittance of PMMA and PC (black and blue) as well as the LED emission spectrum (orange) and the black-body curve for a temperature of 125 °C (dark red). The left panel shows the spectra in the visible range, whereas the right panel shows the near-infrared part. The LED emission spectrum and the black-body curve are each normalized to the maximum intensity and thus not to scale.

Figure 3 shows the transmission spectra of PMMA (black) and PC (blue) in the visible (left) and the near-infrared (right) spectral range. In addition, reflection and scattering spectra are recorded (not shown), so that the absorbance can be estimated. The emission spectrum of the white LED in the visible spectral range is shown on the left in orange color. The spectrum comprises the relatively narrow blue emission at 439 nm from the LED itsself and the broad yellow emission from 470 nm to 750 nm from the phosphor. On the right, the emission spectrum for a black body at a temperature of 125 °C (dark red) is shown for comparison. This represents the infrared radiation from a LED at this temperature.

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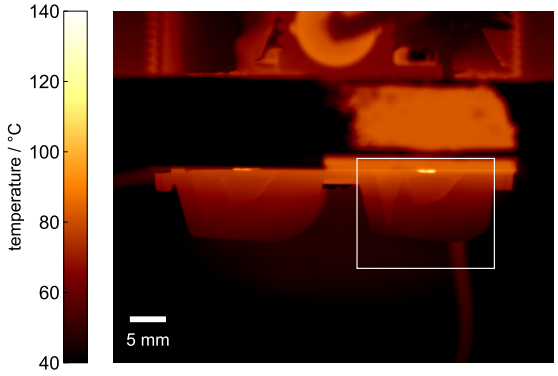

Figure 4: Thermographic image of a cross-sectional cut through the polymer optic (PC). The marked area is shown enlarged in Figure 5. The module is analysed upside down as depicted in Figure 1, bottom part.

Both polymer optics show excellent optical properties in the visible spectral range. The transmittance is almost constant over the entire visible spectral range. At a wavelength of 500 nm, it amounts to 92 % and 90 % for PMMA and PC, respectively. Since the reflectance is 8 % and 10 % for PMMA and PC, respectively, the absorbance is estimated to be in the order of the measurement accuracy of 1 %. However, a more precise knowledge of the absorbance is necessary to allow an accurate estimate of the power absorbed by the polymer. This is of particular importance for high-power LED applications as it is the case here.

The slightly better transmission property of PMMA is due to its lower refractive index, n. At a wavelenth of 500 nm, a typical refractive index of PMMA and PC is $n_{\mathrm{PMMA}} = 1.496$ [4] and $n_{\mathrm{PC}} = 1.597$ [4], respectively. For perpendicular incidence and considering multiple reflections, the resultant transmittance, T, of two polymer interfaces in air ($n_{\mathrm{air}} = 1$) is given by

$$T = \frac{2n}{n^2 + 1}. \qquad (1)$$

This leads to a theoretical transmittance of 92.4 % and 90.0 % for PMMA and PC, respectively. The ultraviolet absorption band of PC is at 394 nm, whereas that of PMMA is deeper in the ultraviolet, i.e., at 373 nm. This might be an issue if the LED emission spectrum has a significant part also in the ultraviolet spectral range.

However, in the near-infrared spectral range the transmittance vanishes for a large part of the spectrum. For both polymers, noticable transmittance is only found for wavelengths shorter than 4 µm. The spectral reflectance (not shown here) is mostly constant in the spectral range investigated and amounts to approximately 7 %. Thus, the black-body radiation, originating from the PCB and the LEDs, is almost completely absorbed for wavelengths longer than 4 µm.

Thermographic imaging of a cross-sectional cut through the polymer optic

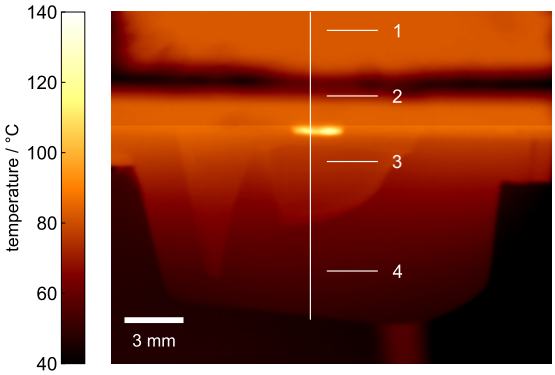

Figure 5: Magnified cross-sectional cut through the secondary optic (PC) as indicated in Figure 4. The temperature profile along the white line is shown in Figure 6.

To measure the temperature profile inside the optic, a cross-sectional cut is fabricated with the surface polished to optical quality. Figure 4 shows the temperature distribution of a cross-sectional cut of one of the investigated optics. The LED module is operated with the optic (indicated by a white frame) facing downwards. Figure 5 enlarges the area of interest. Characteristic positions within the cross-sectional cut are labelled. Position 1 lies within the PCB. Having passed the white-yellowish hotspot from the LED, position 2 indicates a location within the cavity of the optic, while position 3 marks the inner surface of the optic. Position 4 indicates the outer surface of the optic, i.e., the polymer-to-air interface. The vertical white line through the center of the LED serves as reference for the temperature profile inside the optic, as shown in Figure 6.

Analysis of the temperature profile within the polymer optic

For both polymers (PMMA and PC), the temperature profile through the optic can be seen in Figure 6. At the bottom of the cavity ($z = 1.8$ mm), both polymers are at the same temperature of 82 °C. This value is very close to the set board temperature of 85 °C. Within the cavity, the temperature falls linearly down to 67.7 °C and 66.5 °C for PMMA and PC,

respectively, at the boundary to the bulk (z = 5.5 mm). Within the bulk, it becomes more obvious that the temperatures diverge due to the different thermal conductivities of λ_{PMMA} = 0.19 W/(m · K) [5] and λ_{PC} = 0.20 W/(m · K) [6]. At the cavity-to-bulk interface, the temperature shows a slight increase, followed by a significant drop by approximately 7 °C. From there on, the temperature again decreases linearly to 52.6 °C and 49.4 °C for PMMA and PC, respectively, at the outer surface of the optic (z = 10.5 mm).

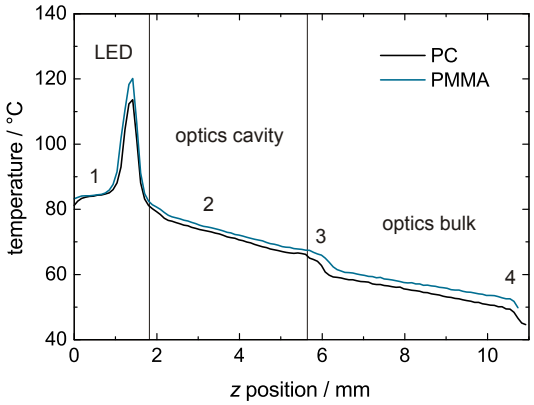

Figure 6: Temperature profile of the investigated PMMA and PC optics. The positions 1 to 4 are consistent to the positions indicated in Figure 5.

Three mechanisms are contributing to the heating of the optic: (i) A significant contribution is given by thermal conduction since the secondary optic is in direct contact with the PCB. The PCB itself is kept at a constant temperature of 85 °C by an external heater. (ii) A further contribution is due to convection. The air within the cavity is heated by the LED and the PCB, and there is convective heat transfer to the cavity-to-bulk interface. (iii) The contribution of radiative heat transfer is negligible. Thermal radiation is typically only important for very hot objects, or for objects with a large temperature difference, which both is not the case here.

Apart from the above-described mechanisms for heat transfer (conduction, convection, and radiation), a significant contribution might be due to absorption of the LED emission in the visible spectral range. Though both polymer optics provide an excellent transmittance in the spectral range of the LED emission, a small, but not negligible part might be absorbed by the optic due to marginal absorption within the optic. Partial absorption of the visible emission is probably the most critical part since the optical output power in the visible spectral range is in the order of several watts, i.e., an absorbance in the order of a few tenths of a percent already results in a heating power of a few milliwatts.

Comparison between cross-sectional cut and complete optic

To prove the suitability of cross-sectional cuts for the temperature profile analysis, a similar experiment is carried out for a complete optic. Again, the LED module is operated with the optic facing downwards. Once the temperature has reached a steady state, the LED module is removed from the optic. During this process, thermographic images are taken every 50 ms. The time scale to remove the LED module is in the order of a few hundreds of milliseconds. For such a short period of time, the temperature of the optic shows only a negligible decrease and is in the order of 0.1 °C. Figure 7 shows the temperature distribution of the inner surface of a complete optic having removed the LED module. At the position of the optics cavity, the temperature at the cavity-to-bulk interface amounts to approximately 66 °C, which is in good aggreement to the measurements at the cross-sectional cuts. The use of cross-sectional cuts is thus a suitable method to investigate the temperature profile within a (polymer) optic.

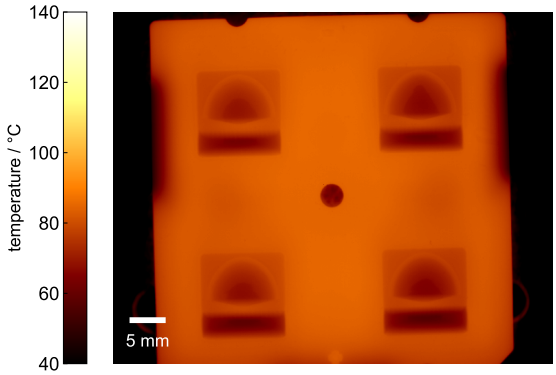

Figure 7: Thermographic image of the inner surface of the polymer optic (PC) after operation facing downwards. The cooler areas on the left and right side of the image are caused by the mounting of the optic.

Conclusions

For the investigated combination of a high-power LED module and a polymer optic, the maximum temperature of the optic lies below the heat distortion temperature of the polymer. However, for smaller distances between LED and optic

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unwanted effects are expected. The results indicate that even a very low absorbance in the visible spectral range might be detrimental, in particular as LED power densities increase. In addition, the transmission properties of the optic need to be carefully matched with the LED emission spectrum.

Acknowledgment

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References

[1] A. Siegmann, M. Narkis, and N. Rosenzweig, Polymer Engineering and Science **19**, 223–225 (1979), doi: https://www.doi.org/10.1002/pen.76019031010.1002/pen.760190310

[2] A. Brydson, Plastics Materials, 7th Edition, Elsevier LTD, Oxford, 1999

[3] W. D. van Driel and X. J. Fan (Eds.), Solid State Lighting Reliability, Springer-Verlag New York, 2013, doi: https://www.doi.org/10.1007/978-1-4614-3067-410.1007/978-1-4614-3067-4

[4] N. Sultanova, S. Kasarova and I. Nikolov, Acta Physica Polonica A **116**, 585–587 (2009), doi: https://www.doi.org/10.12693/APhysPolA.116.58510.12693/APhysPolA.116.585

[5] M. J. Assael, S. Botsios, K. Gialou, I. N. Metaxa, International Journal of Thermophysics **26**, 1595–1609 (2005), doi: https://www.doi.org/10.1007/s10765-005-8106-510.1007/s10765-005-8106-5

[6] J. Blumm and A. Lindemann, High Temperatures – High Pressures, 2003/2007, volume 35/36, pages 627–632

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Light Flicker: A Reasonable Measurement Method in View

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Abstract

Meanwhile, there are some measuring devices to measure light flicker because it has been recognized that fluctuations in the brightness of artificial illumination have a negative effect on the nervous system of humans and other beings. Despite the years after recognizing the need to measure this, there is still no agreement on the measurement method. The only thing that is clear is that a simple amplitude measurement is not enough, but that an analysis and a weighted evaluation of the individual frequencies over a wide range is the right approach. According to this, many of the measuring methods, presented in the meantime worldwide, are not suitable to the compatibility with humans. In fact there are basically only two methods left:

- Compact Flicker Degree CFD
- TLA combining PstLM and SVM

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Light flicker measuring methods

Inappropriate methods are either those operating in the time domain where no frequencies are taken into account at all, or those though operating in the frequency domain, but where the frequency range is insufficient or where there are definition gaps or discontinuities in the frequency range.

Unsuitable methods

The most widespread method according to **IES: RP-16-10** [1] with %flicker (pure amplitude ratios) and flicker index (pure area ratios) is the least suitable method because two values whose combination is not defined are not communicable and also frequencies are not considered at all.

IEEE 1789 [8] only considers the main frequency and the sensitivity functions contain physiologically unexplained discontinuities. In addition, the limits are so sharp that even the low flicker of the European incandescent light bulb is considered dangerous.

The procedure according to California Energy Commission **CEC Title 24 JA10** [5] fails due to the lack of weighting of contained frequencies, which is why a highly noticeable flicker below 25 Hz is considered “low flicker”.

The procedure according to **ASSIST** [2] includes only frequencies up to 70 Hz, thus stroboscopic and phantom array effects are not taken into account.

For the above methods have been analysed within the process for the new European Eco-Design Directive and there considered not suitable [11], they are not discussed in the further course.

Remaining methods

The Compact Flicker Degree (**CFD**) [6][7] continues to be the template for a way to measure, declare and assess light flicker, because the method provides a single percentage value for the entire frequency range effecting on humans with frequency-dependent weighting and without definition gaps or discontinuities.

CIE describes light flicker with the term “Temporal Light Artefact” (**TLA**) [3][4] and proposes the IEC **PstLM** method, which though is not sufficient due to its low cut off frequency. Referred to NEMA 77: 2017 this is supplemented by the CIE **SVM** procedure [12]. The resulting two values for the measurement of light flicker make the communication difficult and a normative setting of application-specific limit values is practically impossible.

This paper deals with the suggestion of a validated smart combination of both values into one, which would make the TLA measurement useful.

In order to complete the discussion on the effects of light modulation, this paper also shows that an additional measurement method for the phantom array effect is superfluous.

The two remaining methods CFD and TLA are up for discussion for the new European Eco-Design Directive and for standardisation by the IEC.

Measuring of the phantom array effect not needed

The phantom array effect (ghosting) is caused by stroboscopic light. The difference is the perspective of the observer: Watching a relatively small light source from a distance with fast eye movements or at different speed to the observer the light appears to be an array of light points. Examples of this are the daytime running lights and rear lights of motor vehicles which lead to irritation [9][10].

So a distinction between the “stroboscopic effect” and the “phantom array effect” may be useful for explanatory purposes. However, for the evaluation of a light source, the assessment and for limit values, there must be no difference for the following reasons:

Imagine the position of an observer standing directly under a street lamp. The street lamp emits its light with 100 Hz rectangle with a duty cycle of 50%. The observer experiences stroboscope light. Now the observer slowly moves away from this lamp (about 300 yards), so that in this bigger distance the light of the street lamp appears to the observer as a small light source. If the observer now quickly moves his eyes (saccades), then he experiences the phantom array effect of this lamp. During the walk away from the lamp, depending

on the distance of the observer from the lamp, each intermediate state between stroboscope light and phantom array effect is possible and thus the light is experienced as a mixture of both.

Additionally: While the cause of “phantom array effect” is stroboscopic light with high contrast containing dark periods of time, the modulation is always above 80%. Consequently it is very unlikely to perceive this effect with a light modulation of 10% (according to CIE [3]). If that was so, even the European incandescent bulb would have become a case of ghosting, which has never been reported.

In contrast to the perception of the stroboscopic effect or even light flicker of lower frequency, the perception of the phantom array effect depends less on the frequency of the light. The perceptibility of the phantom array effect is mostly dependent on the light frequency in so far as the higher the frequency, the eye movements must be faster in order to perceive this effect at all.

By looking into the modulation versus frequency chart (sensitivity), the phantom array effect curve may be moved upwards by a factor of only 2.5. This brings it out of the 10% modulation range and makes it similar to the SVM curve. As a result the measuring method of the phantom array effect is covered by the SVM method.

Thus the phantom array effect curve becomes superfluous.

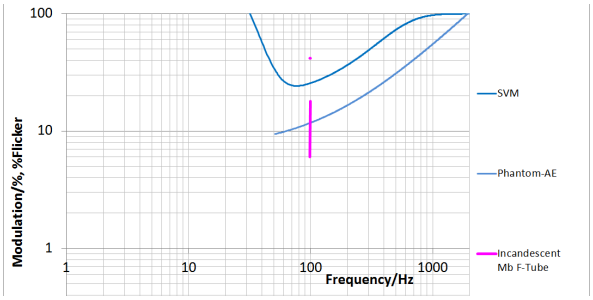

Figure 1: Sensitivity curve of the phantom array effect.

Calculations in frequency domain

For the two remaining methods the calculation in the frequency domain is required.

It has to be emphasized that the method of the frequency analysis has a decisive effect on the

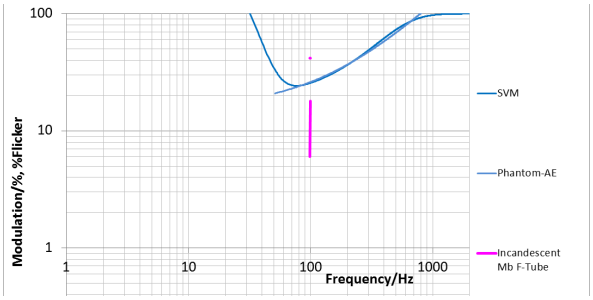

Figure 2: Sensitivity curve of the phantom array effect assimilated by SVM.

result for CFD, PstLM and SVM. Neglecting this aspect might lead to a result error of up to 20% of the final value, because of the high dynamic in the weighting curve.

In order to minimize errors in the summation of the frequency components, the spectral leakage should be absent.

The spectral leakage in continuous-time signal analysis is based on the fact that in reality every signal has a beginning and an end and cannot be continued periodically for an infinite time. The effects of the spectral leakage can be minimized by using appropriate methods such as the use of special windowing filter functions. Depending on the selected window function, this can be virtually completely eliminated in a further operation of the signal analysis.

Requirements for the complete elimination of spectral leakage:

- Signals are examined which contain predominantly periodic signals, which mainly contain a fundamental frequency and associated harmonics.
- A window function is selected whose spectral leakage error is predictable.
- The significant spectral leakage fraction of the window function is limited to a few bins.

The first condition is given in the context of the investigation of the residual ripple of artificial, electrical light sources (light modulation). The modulation components in the signal are usually generated by the infeed (mainly mains voltage) or the internal electronics (e.g., PWM). It may be allowed to assume that noise signals are almost absent, which in turn can be completely eliminated by a downstream noise filter.

The second condition is met when a window function is selected which provides an FFT

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analysis for a signal jump to 1 for the entire signal. The step response is usually a falling, running towards zero curve.

Investigations have shown that the window functions Blackman-3T, Blackman-Nuttall, and Hann are best. This is because the spectral leakage is significantly limited to a few bins and is therefore predictable and can be completely eliminated.

Light modulation calculations performed by Der Lichtpeter fully apply appropriate methods.

CFD method

The Compact Flicker Degree CFD [11] is defined by a single percentage as the final value by calculating the Pythagorean Sum (Euclidean norm or Vector-p-norm with p=2) on the single weighted frequencies.

$$\mathrm{CFD} = \sqrt[2]{\sum_{i=1}^{N} \left(\frac{C_i}{T_i}\right)^2} \qquad (1)$$

where C_i is the normalized amplitude of the i-th Fourier component and T_i is the CFD sensitivity value for the effect for a sine wave at the frequency of the i-th Fourier component. N is limited by the number of samples only.

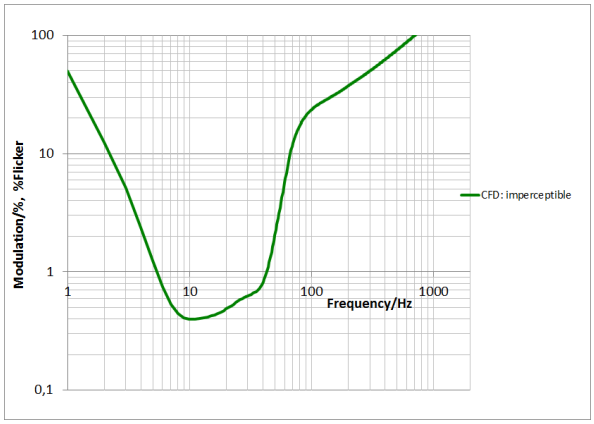

Figure 3: CFD sensitivity curve.

All frequencies for visible and invisible temporal changes in brightness are included in the calculation. The range below 10 Hz is weighted lower to avoid the over-estimation of remaining FFT leakage effects occurring in practice.

For dimmable light sources, the measurement is performed 1st with 100% brightness and 2nd with 25% brightness, the worse of both values is declared as the final value.

The transition from the non-linear frequency range up to about 70 Hz, which is perceptible when situated rested, into the range which is rather perceptible under motion, the CFD performs this as smooth (physiologically plausible).

The CFD given in a single percentage as a comprehensive measurand for modulated light is suitable for declaration and permits categorization according to a traffic light system. The categorization criteria for the CFD depend both on the visibility and on the relevance and risk in the respective application. For example, in a workshop it is essential to avoid stroboscopic effects for the safe operation of rotating machines, whereas they play a little role in walkways, parking lots or storage spaces.

Combination of PstLM and SVM

In order to obtain one single measuring value for TLA without any discontinuity at 60–70 Hz, the two single values for PstLM and SVM have to be merged somehow. The test method and data analysis for the IEC Pst is time domain based and contains statistical calculations whereas the CIE SVM is frequency domain based, which are two very different measuring methods. This would create some complexity in approaches to testing with the development of a modified and calibrated flicker meter required for the IEC part.

So the smart basic idea is to harmonize respectively to convert the IEC Pst calculation method into a PstLM method by operating in frequency domain and by using the same formulas as for the SVM method, but with different weighting characteristics.

As it is possible to represent the PstLM curve in the same chart as the SVM curve, it should be possible to use the frequency response as the sensitivity curve.

Converting the Pst_{IEC} = 1.0 into a Pst_{LM} sensitivity curve

The mathematical polynomial function, determined from the sensitivity curve Pst=1.0

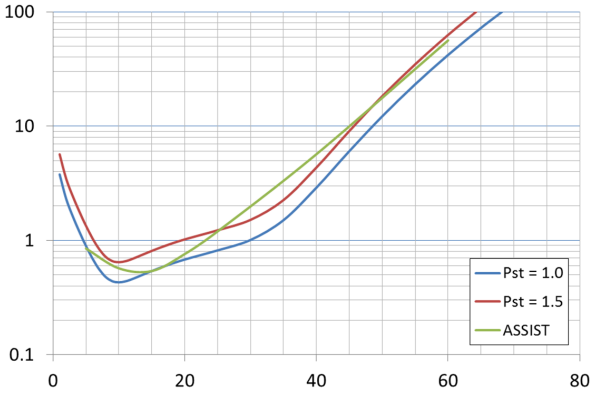

Figure 4: Sensitivity curve Pst=1.0.

([13], page 26) in the modulation versus frequency chart, will be called $Mod_{Pst=1.0}(f)$ below.

Calculating PstLM with the sensitivity $Mod_{Pst=1.0}(f)$

The calculation method is applied in the same manner as for CIE SVM[4]:

$$PstLM = \sqrt[3.7]{\sum_{i=1}^{N(\leq 2\,kHz)} \left(\frac{C_i}{T_i}\right)^{3.7}} \qquad (2)$$

where C_i is the normalized amplitude of the i-th Fourier component and T_i is the PstLM sensitivity value $Mod_{Pst=1.0}(f)$ for the effect for a sine wave at the frequency of the i-th Fourier component.

Verifying harmonized PstLM against IEC Pst

The method has been verified by calculating 18 different waveforms in flicker frequency range (below 70 Hz) against a reference flicker meter. The deviation is $\leq$ 3%.

Combining the sensitivity curves of PstLM and SVM

After the calculation method for PstLM has been verified, it is now possible to combine the sensitivity values for each frequency by merging each single value $T_{PstLM}(f)$ and $T_{SVM}(f)$ using the vector-p-norm inversely proportional. p has been chosen 1.5 to get the best compromise between modifying the two single sensitivity curves as little as possible and closing the discontinuity gap by a steadily rising piece (according to the humans sensitivity decreasing with higher frequency).

$$T_{TLA}(f) = \sqrt[1.5]{T_{PstLM}(f)^{-1.5} + T_{SVM}(f)^{-1.5}} \qquad (3)$$

where $T_{SVM}(f)$ is the sensitivity for SVM according to CIE TN 006:2016 [3] and $T_{PstLM}(f)$ is the PstLM sensitivity $Mod_{Pst=1.0}(f)$ from above.

This merging method results in the following sensitivity curve:

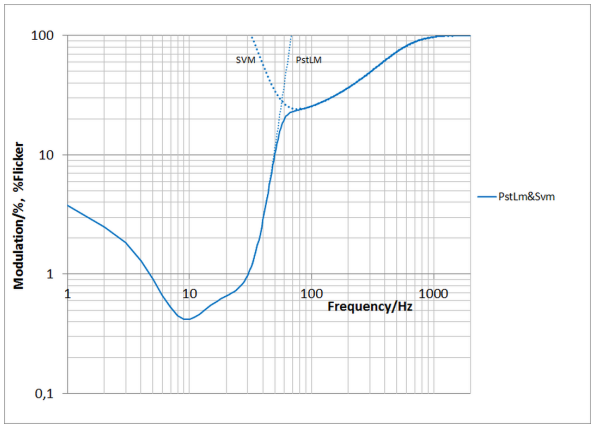

Figure 5: Sensitivity curve of PstLM merged with SVM.

Calculating TLA with the combined sensitivity

The calculation method is again the same as for CIE SVM:

$$TLA = \sqrt[3.7]{\sum_{i=1}^{N(\leq 2\,kHz)} \left(\frac{C_i}{T_i}\right)^{3.7}} \qquad (4)$$

where C_i is the normalized amplitude of the i-th Fourier component and T_i is the combined sensitivity value $T_{TLA}(f)$ for the effect for a sine wave at the frequency of the i-th Fourier component.

Overview including the CFD

The PstLM&SVM curve now comprises the single values for PstLM as the replacement for IEC Pst, SVM and also phantom array effect, for the latter has been assimilated by SVM and thus regarded to be superfluous as an extra value.

One can see now, that PstLM&SVM curve and the CFD curve are not very far away from each other.

Nevertheless the TLA calculation using the vector-p-norm with p=3.7 has the advantage to be

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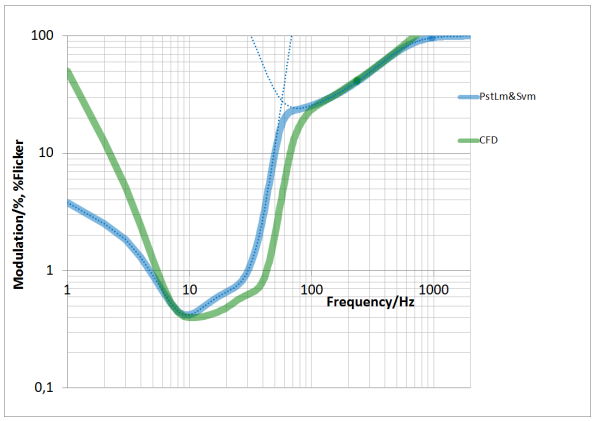

Figure 6: Sensitivity curves of TLA (PstLM&SVM) and CFD.

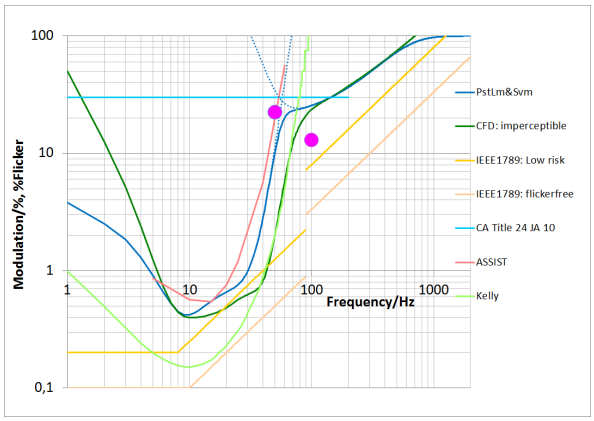

Figure 8: CFD = 139% PstLM = 1.85; SVM = 0.72; PstLM&SVM = 2.11.

more tolerant of spectral leakage evoked by FFT using window functions.

On the other hand a high p value tends to rate mainly the fundamental frequency and thus neglects the waveform much more than the CFD calculation method does with p=2 [11].

Example

This example shows a light signal in a chart including other known sensitivity curves.

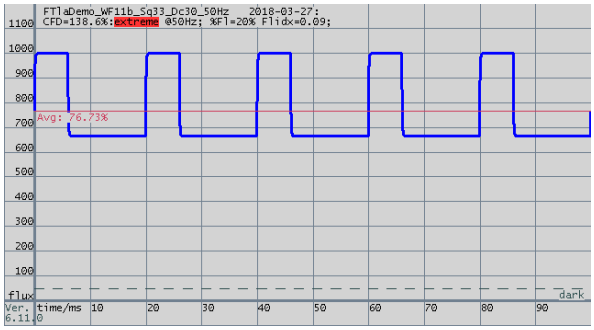

Figure 7: Signal: Square, 50 Hz, DC=30%, MD=20%.

FFT analysis (normalized to DC=1.0):

@50 Hz: 0.1123 (–18.99 dB; MD=22.46%) *
@100 Hz: 0.0655 (–23.68 dB; MD=13.1%) *
@150 Hz: 0.0134 (–37.44 dB; MD=2.68%)
@200 Hz: 0.0209 (–33.59 dB; MD=4.18%)
@250 Hz: 0.0276 (–31.18 dB; MD=5.52%)
@300 Hz: 0.0129 (–37.82 dB; MD=2.58%)
@400 Hz: 0.0166 (–35.59 dB; MD=3.32%)
@450 Hz: 0.0119 (–38.49 dB; MD=2.38%)

(*) Values displayed in next graphic (Figure 8)

Other Aspects

Whether dimming by leading edge, trailing edge or PWM (also spread spectrum): The final value can be obtained by either performing several measurements in the dimmed state or a single measurement at given brightness (50% or 25% as with the CFD) and drawing on the worst value.

Control gears may be tested separately in conjunction with a load the DUT is specified for.

Test against mains flicker may be enhanced by stimulating the DUT. Thus for example by adding a rectangular wave shape with 20 Hz or 8.8 Hz modulated with 0.5%. The limitation value should be based on the behaviour of a 60 W incandescent bulb.

In addition to the visible effects, temporal modulations of light can also cause adverse interference with technical equipment. Known examples include striped image interference in any cameras in cases where the shot object is illuminated with stroboscopic light caused by PWM-dimmed LED systems or LED driver systems working without capacitors. Other disturbances may occur with barcode readers, pulse oximeters, sensors, optical measurement laboratories, light barriers etc.

These special cases should be treated separately or in general stroboscopic light of any frequency should be avoided or light modulation should be minimized accordingly.

Apart from all this, as humans we should not forget other sentient beings on earth like birds, nocturnal animals. Therefore general limitations

should be set to MD $\leq$ 50%, TLA $\leq$ 1.5, CFD $\leq$ 25%.

Conclusions

It is necessary to measure and assess light for illumination or static information purposes with respect to all modulations affecting humans and other beings. For this all frequency components should be considered at least up to 2 kHz, better up to 20 kHz. Consequently, the calculation is possible only in the frequency domain, whereby at best each individual frequency is weighted according to the influence on the human being. According to human perception, the weighting curve does not contain any definition gaps or discontinuities.

For the declaration in the technical data or on the packaging, a single measurement is best suited. Several measurements for the same annoyance — the effect of light modulation on humans — are poorly communicable. In addition, the use of a single measure also makes it clearly easier to define normative application-dependent limit values.

As presented in this paper only the Compact Flicker Degree CFD and TLA as a combination of PstLM and SVM fulfill these requirements.

References

[1] Mark S. Rea, IESNA Lighting Handbook: Reference and Application 9th edition, Year 2000 Book ISBN 978-0-87995-150-4

[2] Lighting Research Center; Rensselaer Polytechnic Institute, ASSIST: Recommended metric for assessing the direct perception of light source flicker, Volume 11, Issue 3; Jan 2014 http://www.lrc.rpi.edu/programs/solidstate/assist/pdf/AR-FlickerMetric.pdfWeb, Last call: 2016-05-20

[3] CIE: TC 1-83, D. Sekulovski (Chair), Visual Aspects of Time-Modulated Lighting Systems — Definitions and Measurement Models, Aug 2016 http://files.cie.co.at/883_CIE_TN_006-2016.pdfWeb, Last call: 2017-08-23

[4] ZVEI — German Electrical and Electronic Manufacturers' Association, Lighting Division, White Paper: Temporal Light Artefacts — TLA: Flicker and Stroboscopic Effect, Mar 2017 https://www.zvei.org/fileadmin/user_upload/Presse_und_Medien/Publikationen/2017/Maerz/ZVEI_White_Paper_Temporal_Light_Artefacts_English_Download_2017_05_05/ZVEI_White_Paper_Temporal_Light_Artefacts_-_English_-_Download_-_2017-05-05.pdfWeb, Last call: 2018-04-23

[5] California Energy Commission, Edmund G. Brown, Reference Appendices for the 2016 Building Energy Efficiency Standards Title 24, Part 6, Jun, 2015 http://www.energy.ca.gov/2015publications/CEC-400-2015-038/CEC-400-2015-038-CMF.pdfWeb, Last call: 2017-08-23

[6] Der Lichtpeter, Peter Erwin, elektroboerse-smarthouse: Lichtflimmern: Ursache und richtige Vermessung, Feb 2017 http://www.elektroboerse-smarthouse.de/elektroinstallation/beleuchtung/artikel/138700/Web, Last call: 2017-08-23

[7] Der Lichtpeter, Peter Erwin + Photoalume Peter W. Shackle, LEDs Magazine: Understand a new flicker metric and its application to AC-LED light engines, Apr 2017 http://digital.ledsmagazine.com/ledsmagazine/201704?sub_id=2pw63KKId0D0&u1=DA0417Web, Last call: 2017-08-23

[8] IEEE Standard Association, IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers, Mar 2015 http://www.bio-licht.org/02_resources/info_ieee_2015_standards-1789.pdfWeb, Last call: 2017-08-23

[9] Dr. Dmitrij Polin, Flimmereffekte von pulsweiten-modulierter LED-Beleuchtung, Mar 2012 http://tuprints.ulb.tu-darmstadt.de/4664/1/DissertationDmitrijPolinFlimmereffektevonpulsweiten-modulierterLED-Beleuchtung.pdfWeb, Last call: 2017-08-23

[10] European Commission, DG Health and Food Safety, Preliminary Opinion on Potential risks to human health of Light Emitting Diodes (LEDs), Jul 2017 https://ec.europa.eu/health/sites/health/files/scientific_committees/scheer/docs/scheer_o_011.pdfWeb, Last call: 2017-10-29

[11] Der Lichtpeter, Peter Erwin, EuP-Proposal for the new EU Eco-Design Directive, Nov 2017 http://www.eup-network.de/fileadmin/user_upload/Lichtquellen_Flimmern_Erwin_2017_10_EN.pdfWeb, 2018-04-29

 © 2018 Luger Research e.U.

[12] Michael Jouaneh, Lutron Electronics Co., Inc, Comments on the 2019 Title 24 Part 6 Building Energy Efficiency Standards 45-Day Language, Feb 2018 https://www.energystar.gov/sites/default/files/LampsVersion21Draft---CommentSummaryandResponse.pdfWeb, Last call: 2018-04-29

[13] Ethan Biery, Lutron Electronics + Jim Gaines, Philips Lighting Lightfair International, Presentation: Measuring What's Hard to Describe, Apr 2016 http://bonlacfoods.com/pdf/018563711.pdfWeb, Last call: 2018-04-29

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Human Centric Lighting II

528 Effects of Temporally Modulated Illumination to Human Beings: Nine Statements from a Research Perspective
by DI MMag. Markus Canazei, Bartenbach

536 Miniaturization and Its Consequences
by MLL Marcel Hubeli, Bartenbach

Effects of Temporally Modulated Illumination to Human Beings: Nine Statements from a Research Perspective

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Abstract

Light sources, which are temporally modulated in emitted radiation, may induce several direct perceivably artefacts to human beings, for instance, visual unsteadiness in intensity or spectrum of light (flicker effect), in motion (stroboscopic effect) or in perceived shape or spatial position of objects (phantom array effect). Several experiments with LED light sources have been conducted recently, within which visibility thresholds for flicker and stroboscopic effects were derived.

Studies over the past 60 years have clearly shown that three factors (related to the luminaire, subject and environment) mainly contribute to the occurrence of visible as well as non-visible effects of temporally modulated lights. Today there is evidence, that the amount, frequency and modulation depth of the emitted light, the size of the light emitting surface, the spatial position of the luminaire within the field of view, the age and arousal level of the exposed subject, and fast moving objects (e.g., at industrial workplaces, in sports, on roadways), fast eye movements (e.g., during proof-reading) or fast head movements play a crucial role.

Published methods and metrics [1] and design recommendations from the International Commission on Illumination [2] and the German Electrical & Electronic Industry [3] take perceivable effects of temporally modulated illumination of up to 2000 Hz after short exposure into account. However, distinct detrimental effects on human beings have been derived from imperceptible light modulation during extended exposure to either fluorescent lamps or CRT display light.

In the following, human impact research on temporally modulated lights is critically summarized in nine statements. Furthermore, core limitations of studies with different LED control strategies are described and topics for future investigations are outlined.

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Statement: So far, primarily technology leaps but not research, have been triggering improved quality criteria for lamp operation. It looks like this story will be repeated with LED technology.

Basic research on physiological effects of perceivable flicker effects started in the sixties of the last century [4][5][6]. At that time, first studies on flicker effects of fluorescent lamps were also carried out [7][8]. With widespread market penetration of this lamp technology in the 1980's and 1990's, research intensified and focused on measuring invisible flicker effects generated by luminaires in the peripheral visual field [9]. These studies showed that subjects were cognitively, subjectively and visually less impaired when working under lamps mainly operated with frequencies higher than 20 kHz [10]. Our research institute also conducted studies on magnetic and electronic ballasts of fluorescent lamps in the 1980s. In these studies, we could measure negative effects of magnetic ballasts on several visual performance parameters.

After the advent of personal computers as working tool in the late 1980s, research on flicker effects of cathode ray tube (CRT) displays began in the early 1990s [11][12][13]. Finally, after installation of the first LED room lighting systems around the turn of the millennium, research on visible effects of LED operation started in 2005 [14].

This short historical review should illustrate that research on detrimental effects of lamp operation rarely started with market entry of this technology but after it had gained a significant market share. To put it another way: **high-quality lamp operation, aiming to avoid moderate to low risks to humans, is a low-ranked quality criteria** compared to other quality criteria such as the luminous efficiency, cost, longevity, and spectral quality of the light source. It can further be hypothesized that anecdotal evidence from end-users, who noticed adverse effects of lamp operation in daily life, were one driving force to conduct impact research on lamp operation. Finally, it seems that primarily leaps in technology, not research results, facilitated the establishment of new quality standards for lamp operation.

At present, LED technology captures the lighting market in all application areas of illumination. Due to their energy efficiency and longevity, LEDs have a decisive market advantage over other previously dominant light technology, such as fluorescent lamps. Today, two different LED control topologies (constant current and constant voltage drivers) are offered at the market. When LEDs should be dimmable to low light levels, pulse width modulation (PWM) in constant voltage drivers is used. These drivers usually operate at frequencies between 200–500 Hz. Driven by studies on visible flicker and stroboscopic effects [15], higher-quality ballasts today operate at frequencies above 1000 Hz or reduce the modulation depth when operating at lower frequencies.

Quality standards in the operation of LEDs are currently based on the prevention of detrimental visible effects [16]. Although studies with ballasts of fluorescent lamps have clearly shown that invisible flicker affects people, this knowledge so far did not influence the specification of LED control gears. It may be assumed that yet again it requires a leap in LED driver technology to define higher-quality light control standards which also prevent invisible flicker effects.

Statement: A multitude of influencing factors contribute to the diverse negative effects of lamp operation in humans. For this reason, it is hardly possible to derive specifications for high-quality lamp drivers today.

Studies could show that a multitude of aspects, related to lamp operation, the luminaire, the environment and even humans play a crucial role in the conscious perception of temporally modulated light. At least the following 13 influencing parameters, assignable to the four factors, can be listed:

lamp operation factors: frequency, modulation depth, duty cycle, and waveform shape [17]

luminaire-related factors: area of the light emitting surface, direct view of the light source, and emitted light spectrum [18]

environmental factors: position of the luminaire within the field of view, visual task load, cognitive task load, adaptation level, local contrast between light source and immediate surrounding, and exposure duration, and [19][20]

human-related factors: sensitivity for flickering lights (e.g., photosensitive seizure), age, and arousal level [21][22]

At present, it is unknown which of these 13 factors and to what extent they are also contributing to the emergence of adverse invisible flicker effects.

The multitude of influencing factors which are independent of lamp operation-related factors (e.g. luminaire-, environmental and human-related factors) aggravates the specification of improved lamp driver quality.

Consequently, although research so far validated improved operating quality of new products, knowledge generated by research influenced the specification of lamp operation to a minor extent.

Statement: Known adverse effects of lamp operation can be assigned to three risk classes. Today's standards focus only on severe risks.

We recommend the categorization of adverse effects of temporally modulated lights into the following three risk classes:

Risk class 1 (mild):

Lamp operation is associated with asthenopic complaints, e.g., blurred vision, occasional double vision, fatigue, inability to maintain a clear image leading to headache or eye related pain, and burning, watery, or dry eyes. Listed symptoms are transient and occur when working on tedious visual tasks over an extended period. Research on the relationship between lamp operation and asthenopic complaints is done in lab studies [21][23] and is accompanied by reports of susceptible subgroups (e.g., migraineurs) [24][25].

Risk class 2 (harmful):

Lamp operation reduces visual and cognitive performance measures [19], impairs the oculo-motoric behavior under visual load [26] and triggers physiological reactions (e.g., cortical hyperactivity [27]). A cause-effect relationship between the light stimulus and its detrimental effects can be derived after prolonged exposure (several minutes to hours) to the light stimulus. Research of harmful effects consists of investigating primarily invisible effects of temporally modulated lights within controlled lab studies.

Risk class 3 (severe):

Lamp operation immediately (within seconds) triggers adverse health effects (e.g. photosensitive epileptic seizure, migraine [21][24]), or generates occupational risks (e.g. impaired visibility of moving objects) or road risks (e.g. distraction of drivers by stroboscopic and phantom array effects). There exists a direct cause-effect relationship between the light stimulus and its detrimental effects.

Current recommendations for operating LEDs aim at avoiding short-term, visible health-related effects of risk class 3. In contrast, adverse effects of LEDs within risk class 1 and 2 have yet not been sufficiently investigated.

We advise investigating **negative effects of LED lamp operation thoroughly within all three risk classes and update current recommendations.**

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Statement: Today, impact research on LED drivers is essentially based on the flicker-fusion paradigm. Other methods are time-consuming and so far have not been used to quantify detrimental effects of LED lighting.

Flicker fusion occurs when an intermittent light stimulus appears to be steady to a human observer. Flicker fusion thus characterizes the borderline between visible and invisible luminous modulation of light sources.

By applying this flicker-fusion paradigm to dynamic scenarios, e.g. staring at a white dot on a fast rotating black disks [28], under fast reacting LED light sources, it could be shown that humans are able to perceive discontinuous motion effects at operation frequencies of up to 10 000 Hz [29].

These effects arise instantaneously, represent severe (health) risks to humans and thus should definitely be avoided. However, particularly effects of invisible flicker after prolonged exposure to temporally modulated LED light, measured with **visual and cognitive performance tests and physiological parameters**, may as well pose a risk to the well-being of humans and their ability to work.

There is an urgent need to know all possible detrimental consequences of non-visible flicker to humans caused by LED drivers.

Statement: Visibility thresholds for flicker and stroboscopic effects are known today. Invisible flicker effects of LEDs have not been investigated so far and thus are not considered in recommendations for LED drivers.

Today, three visible effects of temporally modulated LED lights have been described:

Flicker effects (i.e. visual unsteadiness in light emission or illumination) are generated by lamps which are operated with a frequency lower than 80 Hz and occur in a static environment for a static observer. Humans are most sensitive to flickering lights between 10–20 Hz.

Stroboscopic effects (i.e. perceiving discrete images of moving objects) arise in non-static environments for static observers and are perceivable even at frequencies up to 10 000 Hz. Interestingly, stroboscopic effects have hardly be investigated in the past (e.g. under fluorescent lighting) but became an important research topic for LED lighting recently.

Phantom array effects are perceived as changes in shape or spatial position of objects under mesopic and scotopic light levels. Studies could show that these effects may arise at frequencies above 1000 Hz during saccades (i.e. quick eye movements between fixations) and head movements [30].

Recently, IEEE PAR 1789 [10][15] as well as CIE [2] and IEC [1] defined key metrics and offered solid-state lighting product developers guidance on how to ensure that LED-based products should be operated to avoid undesirable health effects. Given recommendations aim at controlling the probability to perceive flicker and stroboscopic effects (i.e., the 50% detection limit is defined as perception limit) but do not take phantom array effects into account. Experts from the working group IEEE PAR 1789 estimated invisible flicker

effects from LEDs after prolonged exposure with a moderate to low (health) risk for humans. Although this working group pointed out in 2015 that further research is needed, no studies on invisible flicker effects under natural conditions have been published to date.

Due to the estimated low risk profile and missing scientific evidence, invisible flicker effects are not considered in current recommendations. However, since studies clearly showed that invisible flicker under fluorescent lighting negatively affected humans [17][32][33], it can be assumed that these adverse effects may also occur under LED lights, which emit light faster and with no persistence compared to conventional light technologies and thus should be considered in future recommendations.

Statement: Radiation overlapping of two independently operated light sources may produce visible beat and chromatic flicker effects. Risks of these effects are currently unknown.

So far, studies have investigated the effects of a single, temporarily modulated light source on human beings. Using one light source is a very simplistic study setup compared to the use of many luminaires in everyday room lighting.

LED lighting installation comprise multiple light sources and luminaires whose lamp operation is not synchronized. In a special mockup, shown in our booth at LPS 2018 (Figure 1), we are able to show that concurrent operation of two non-synchronized temporally modulated LED light sources generate **visible beating effects**. To our knowledge, end-users so far have not complained about beating effects from LED lighting systems and no study has investigated visible beating effects of two asynchronous operated LED light sources.

In addition, human-centric lighting concepts, which comprise tunable white lights, generate a second application scenario in which visible, so far unnoticed, flicker effects of overlapping LED

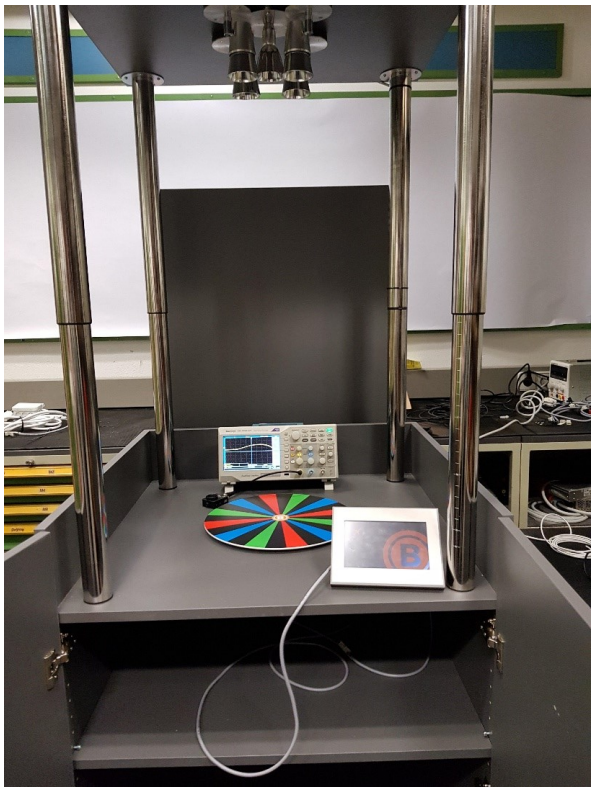

Figure 1: Mock-up to demonstrate visible beating and chromatic flicker effects

radiation may occur. Operating two different light colors within one luminaire independently, may cause **visible chromatic flicker effects** (Figure 2). Again, we so far have not got customer feedback from our own lighting design projects with tunable white solutions indicating this problem nor do we know studies which demonstrated visible chromatic flicker within lab studies.

Statement: We identified five main limitations of impact research on LED drivers and hereinafter recommend appropriate countermeasures.

Current test methods strongly focus on implementing objective and reliable test procedures to measure acute visible effects and take special care to optimize test efficiency, i.e., to quantify effects of many test conditions in short time periods with low visual and cognitive load to humans. Below, five limitations of impact research on LED drivers are highlighted.

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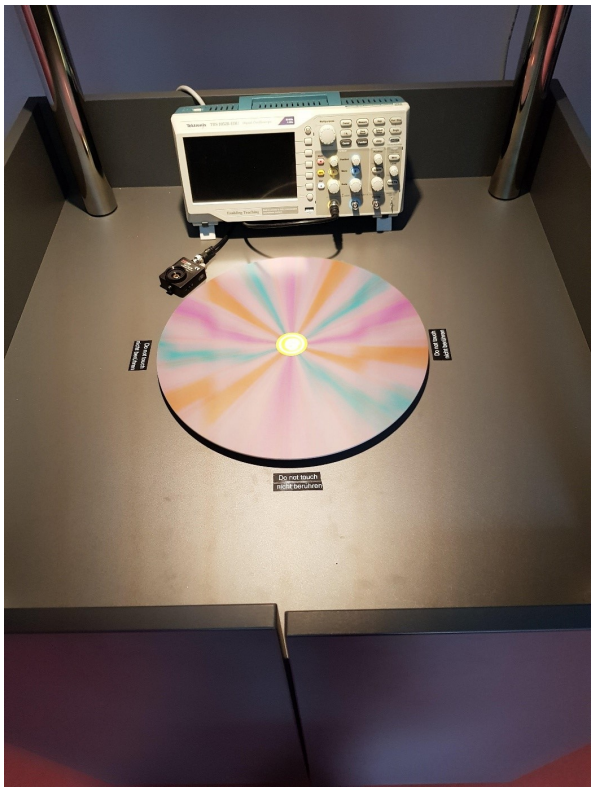

Figure 2: Chromatic Flicker Effects

Limitation 1: use of limited set of measures.

Today, primarily the visibility of flicker and stroboscopic effects and acceptance ratings under fixed gaze have been recorded [16]. We recommend the use of the following additional measures under natural viewing conditions: cognitive and visual performance parameters (focussing on attention processes and visual search tasks), physiological parameters (gaze behavior, cortical activation, activation of the hypothalamic pituitary-adrenal axis, activation of the autonomous nervous system) and asthenopic complaints.

Limitation 2: very short exposure duration.

Subjects, participating in studies which investigate flicker and stroboscopic effects, work on visual tasks only a few seconds. Furthermore, acceptance ratings are collected immediately after this short-term exposure and thus do not make it possible to measure asthenopic complaints. We recommend exposing subjects to temporally modulated lights for several hours and quantify long-term adverse effects several times during exposure.

Limitation 3: exposure to a single, temporally modulated light source.

We recommend the investigation of visible beating and chromatic flicker effects of tuneable-white light solution with independently controlled light sources of different color temperature as well as of at least two independently controlled luminaires. . In any case, this evaluation should contain the dimmed operation (e.g. $<$5% dimming level) of LEDs as well.

Limitation 4: selection of standard observers.

So far, standard observers (i.e., healthy subjects between 20–40 years with no visual restrictions and not suffering from epilepsy or migraine and having no family history of epilepsy) were enrolled in studies. We recommend the enrolment of the following four vulnerable subgroups, which consist of a significant number of human beings: people with a history of migraine [the one-year prevalence rate of migraineurs in the general population for Western countries ranges from 4 to 25%] and epileptic seizure [70 million people worldwide are affected], people with increased photosensitivity or phobic behavior [e.g., after cataract surgery, while taking photosensitizing medication or subjective photosensitivity with unknown etiology] and children. The evaluation of drop-out rates in these studies should be documented carefully.

Limitation 5: unknown arousal level and cognitive load of subjects.

So far, studies have only been carried out under an unknown cognitive state of subjects. We recommend varying and controlling the arousal level and cognitive load of study participants to better represent daytime-specific and situative sensitivity to temporally modulated light stimuli.

Statement: We identified five main areas with a need for research.

Area 1: Investigate visible beats and chromatic flicker effects.

They are caused by simultaneously operating at least two lamps independently or by driving two light sources (e.g., tuneable white solution) within one luminaire.

Area 2: Investigate long-term effects of invisible flicker.

Studies with fluorescent lamps have clearly shown that invisible flicker can negatively affect people on a visual, cognitive, subjective and even physiological level [19][27][17]. We assumed that detrimental effects also occur when operating LEDs.

Area 3: Investigate effects of temporally modulated light sources on susceptible groups/at-risk population.

It is known that visible flicker light causes seizures in people with photosensitive epilepsy [24]. It is not known how non-visible flicker affects this group. Likewise, there is currently no study that has measured direct flicker effects on people with migraine, increased photosensitivity, and children. The estimation of negative health effects of temporally modulated light cannot be limited to healthy standard observers with unrestricted vision.

Area 4: Investigate the flicker sensitivity of non-human species (a widely unrecognized topic).

It has been reported recently [34][35], that vertebrates with high metabolism and small body size have an increased critical flicker fusion frequency compared to humans. For instance, pigeons have been shown to have a higher threshold than humans (100 Hz vs. 80 Hz). It can be assumed that animals react to temporally modulated lights, e.g., in the nighttime urban environment or in livestock farming houses.

Area 5: Conduct basic neuroscience research to thoroughly explore physiological and behavioural effects of temporally modulated light sources.

Technology leaps have so far initiated the establishment of quality criteria for operating lighting technologies. There is a need to better understand the mechanisms of action of flickering light in humans.

Statement: Current quality standards are probably not sufficient.

It has been shown that with rising operation frequency, the modulation depth, duty cycle and form of light modulation play an increasingly minor role in operating lamps [15].

Consequently, IEEE PAR 17 recommended operation frequencies above 3 kHz, independent of modulation depth, because at these frequencies negative health effects in humans are not expected.

More recent recommendations, published for instance by the German Electrical & Electronic Industry (ZVEI) [3], follow new metrics to characterize flicker and stroboscopic effects. These metrics describe visible effects by a summation of the Fourier frequency components of temporally modulated lights operated with frequencies up to 2000 Hz and give clear recommendations for visibility thresholds. **From a research perspective, limits for visible flicker effects under short-term exposure are insufficient to define quality standards for LED lamp operation.** Based on studies with invisible flicker effects of magnetic and electronic ballasts in fluorescent lamps, we suspect that the **safe zone for the operation of LEDs will be at main driving frequencies between 20–100 kHz** independent of other known factors (e.g., modulation depth, duty cycle, waveform shape). This assumption must be confirmed with research, which takes Statement 8 and Statement 9 of this manuscript into account.

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References

[1] IEC TR 63158 (2018). Equipment for general lighting purposes – Objective test method for stroboscopic effects of lighting equipment. Technical Report, 2018-03-19.

[2] CIE TN 006 (2016): Visual aspects of time-modulated lighting systems – definitions and measurement models. Retrieved from: http://files.cie.co.at/883_CIE_TN_006-2016.pdf (10th August, 2018)

[3] ZVEI (2017): Temporal Light Artefacts – TLA. Flimmern und Stroboskopeffekt. Retreived from: https://www.zvei.org/presse-medien/publikationen/temporal-light-artefacts-tla/ (10th August, 2018)

[4] de Lange, H. (1961): Eye's Response at Flicker Fusion to Square-Wave Modulation of a Test Field Surrounded by a Large Steady Field of Equal Mean Luminance. Journal of the Optical Society of America, 51(4), 415-421.

[5] Sperling, G. (1964): Linear theory and the psychophysics of flicker. Documenta Opthalmologica, 18, 3-15.

[6] West, D., Boyce, P. (1968): The effect of flicker on eye movements. Vision Research, 8, 171-192.

[7] Eastman, A., Campbell, J. (1952): Stroboscopic and Flicker Effects from Fluorescent Lamps. Illum. Eng., 47, 27-34.

[8] Rey, P. et al. (1963): Comparison of the effects of two fluorescent lights on a visual task and fatigue test. Ergonomics, 6, 393-401.

[9] Veitch, J. et al. (2001): A critical examination of perceptual and cognitive effects attributed to full-spectrum fluorescent lighting. Ergonomics, 44, 255-279.

[10] Wilkins, A., Clark, C. (1990): Modulation of light from fluorescent lamps. Lighting Research and Technology, 22(2), 103-109.

[11] Farrell, J. et al. (1987): Predicting flicker thresholds for video display terminals. Proceedings of the SID, 28, 449-453.

[12] Ishiguro, Y. et al. (2004): Follow-up survey on seizures induced by animated cartoon TV program "Pocket Monster". Epilepsia, 45(4), 377-383.

[13] Bullough, J. et. al.(2006): Impact of Surrounding Illumination Visual Fatigue and Eyestrain While Viewing Television. Journal of Applied Sciences, 6(8), 1664-1670.

[14] Wilkins, A. et. al. (2010): LED Lighting Flicker and Potential Health Concerns: IEEE Standard PAR1789 Update. Proceedings IEEE Energy Conversion Congress, 12-16 Sept 2010; Atlanta.

[15] Lehman, B. & Wilkins, A. (2014): Design to mitigate effects of flicker in LED lighting: Reducing risks to health and safety. Power Electronics Magazine, 1(3), 18-26.

[16] CIE TN 008 (2017): Final Report: CIE Stakeholder Workshop for temporal light modulation standards for lighting systems.

[17] Veitch, J., McColl, S. (1995): Modulation of fluorescent light: flicker rate and light source effects on visual performance and visual comfort. Lighting Research and Technology, 27, 243-256.

[18] Brindley, G. (1974): Human sensitivity to flicker. Lighting Research and Technology, 6, 127-143.

[19] Kueller, R., Laike, T. (1998): The impact of flicker from fluorescent lighting on well-being, performance and physiological arousal. Ergonomics, 41(4), 433-447.

[20] Carmel, D. et.al. (2007): Perceptual load modulates conscious flicker perception. Journal of Vision, 7(14), 1–13.

[21] Wilkins, A. et al. (1989): Fluorescent lighting, headaches and eyestrain. Lighting Research and Technology, 21, 11-18.

[22] Delaney, S.. et al (2001): The Effect of Flicker Rate on Measured Visual Field Extent in Very Young Children. Optometry & Vision Science, 78(11), 846-852.

[23] Lindner, H. et al. (1993): Asthenopic complaints associated with fluorescent lamp illumination the role of individual disposition. Lighting Research and Technology, 25, 59-69.

[24] Harding, G. & Jeavons, P. (1994): Photosensitive Epilepsy. Mac Keith Press, London.

[25] Colestone, D. et al. (1995): Responses to temporal visual stimuli in migraine CFF-test. Cephalalgia, 15, 396-398.

[26] Kennedy; Wayne S. Murray (1991): The effects of flicker on eye movement control. Q J Exp Psychol A., 43(1), 79-99.

[27] Kueller, R., Wetterberg, L. (1993): Melatonin, cortisol, EEG, ECG and subjective comfort in healthy humans impact of two fluorescent lamp types at two light intensities. Lighting Research and Technology, 25, 71-81.

[28] Perz, M. et al. (2015): Modeling the visibility of the stroboscopic effect occurring in temporally modulated light systems. Lighting Research and Technology, 47(3), 281-300.

[29] ASSIST (2012): ASSIST recommends . . . Flicker Parameters for Reducing Stroboscopic Effects from Solid-State Lighting Systems. Lighting Research Center, 11 (1). Troy, N.Y.

[30] Lee, C. et al. (2017): Phantom array and stroboscopic effects of a time-modulated moving light source during saccadic eye movement. Lighting Research and Technology, 50(5), 772-786.

[31] Veitch, J., McColl, S. (1995): On the modulation of fluorescent light: Flicker rate and spectral distribution effects on visual performance and visual comfort. Lighting Research and Technology, 27, 243-256.

[32] Shady, S. et al (2004): Adaptation from invisible flicker. PNAS, 101(14), 5170–5173.

[33] Jaen, M. et al (2005): Office workers's visual performance and temporal modulation of fluorescent ligting. Leukos, 1(4), 27-46.

[34] Inger, R. et al. (2014): Potential biological and ecological effects of flickering artificial lights. PlosOne, 9(5), e98631.

[35] Healy, K. et al. (2013): Metabolic rate and body size are linked with perception of temporal information. Animal Behavior, 86(4), 685-696.

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Miniaturization and Its Consequences

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Abstract

“Light is not visible, light makes visible”, this also means that the room should be lit and the luminaires step into the background. In modern lighting solutions the luminaires are often no longer visible as they are integrated into the architecture, e.g., combined with acoustic absorbers or cooling ceilings. LED technology makes it possible to use very small optics, but at the same time, all other components of the luminaires must also be smaller to exploit this miniaturization potential. In order to enable miniaturization while keeping high quality of light, Nordic Power Converters have developed a new technology enabling LED drivers to operate at highly elevated frequencies. This leads to a significant reduction in size of the components used in the LED driver while keeping both good mains performance and high quality of light.

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Introduction

"Human Centric Lighting" (HCL), "Smart Lighting", "Biodynamic Lighting" and many more keywords nowadays contribute to the fact that lighting not only supports vision but also influences human emotions, physiology and health. However, clear lighting design recommendations for HCL solutions are still missing and consequently, a huge variety of lighting designs are promoted under the label of being supportive to human health.

HCL concepts aim at providing the right light at the right time, in the right light color and intensity at eye level of subjects. Furthermore, these lighting concepts should not deploy negative effects on vision (e.g., by causing discomfort or disability glare) and visual comfort. Finally, luminaire aesthetics and integration of the luminaires into room architecture are of relevance.

Based on our own research and extensive lighting design experience, we have established a lighting design model (the so-called "theoretical luminance model for indoor illumination") which supports vision as well as creates a harmonic light atmosphere. Furthermore, this model allows to derive luminance levels of all room surfaces which is an important starting point in the lighting design process Figure 1.

Applying this lighting design model often necessitates the installation of several luminaires within a room (e.g., for task and ambient lighting). However, the obtained lighting atmosphere take care for a good balance between delivering vertical brightness (needed for non-visual light effects) and glare-free lighting.

Miniaturization of Luminaires

Thanks to the compact design of LED technology, it is now possible to produce very small light emitters, which deliver tunable white light (a prerequisite for HCL concepts). Furthermore, today we are able to calculate and manufacture compact optical systems for LEDs (e.g., reflectors with highly specular complex surfaces and micro-facets). The application of these optical systems allows a precise control of the direction of the light beam. Furthermore, with a steadily increasing efficacy of LEDs, the number of light sources within a luminaire can be reduced. Consequently, this reduction significantly

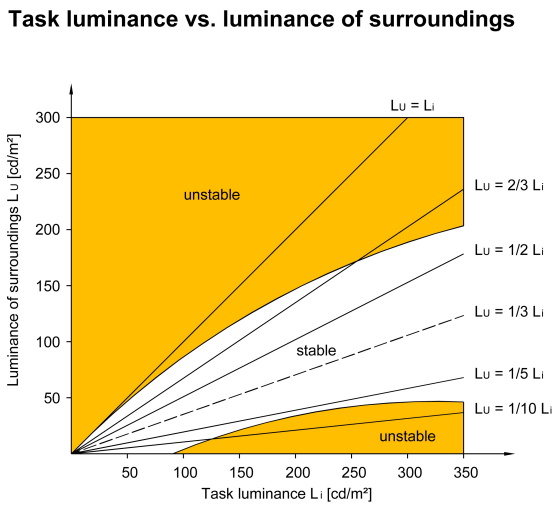

Figure 1: Theoretical luminance model (Source: Bartenbach).

decreases the heat load and allows to reduce the size of the heat sink. In case the luminaire housing is utilized for cooling purposes, today's luminaires can become very small. The small form factor in the end facilitates an easier integration into room design and implementation of lighting concepts which consist of several luminaires Figure 2.

Figure 2: Miniaturized luminaire with lens LFO by Bartenbach.

One component in modern luminaires, which forms the technical basis for realizing such lighting concepts, is often forgotten: the LED driver. Typically, drivers of HCL-luminaires consist of several channels, connection options for sensors or communication modules, and allow the storage of data about the operation of the luminaire. With the steady augmentation of technical requirements for modern LED drivers, this component, although already being one of the largest components of a luminaire, runs the risk to become even larger in its form factor.

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Driver challenges

The majority of quality LED drivers on the market today are so called 2-stage drivers. These drivers are composed of three major blocks:

1. an EMC filter and surge protection
2. an ACDC converter ensuring good mains performance (PF and THD). This block also includes a bulk capacitor storing the 50/100 Hz energy from the mains
3. a DCDC converter which controls the constant current output to the LEDs.

Besides these three parts, the driver also includes control, dimming interfaces etc.

Figure 3: The three major blocks of a quality LED driver.

The quest for miniaturized drivers generally leads to one of three solutions.

Reduced bulk capacitor

The bulk capacitor is one of the largest components in the driver. This component can relatively easily be reduced in size/value, enabling a smaller size of the driver. Doing so will however lead to increased voltage ripple on the bulk which results in increased current ripple/flicker on the output (unless this can be fully suppressed by the DCDC stage).

In the same way it is also possible to decrease the size of many of the big magnetic components. The trade-off here is mainly size and cost against efficiency and thermal stability. In some cases, this trade-off is accepted as this gives a small driver at a reduced cost, but with a low efficiency and shorter lifetime.

Single stage solutions

The second option is to remove the DCDC converter and design for a decent trade-off between mains performance and ripple on the output. In this case the main energy storage to suppress the ripple from the mains is the output capacitor. This works well for a resistive load but imposes a big problem for a LED, because a slight change in voltage can lead to a huge increase in current. For constant voltage solution this can be a solution, as a resistor is often added in series with the LEDs to ensure evenly distribution of the current. For constant current solutions it will however be almost impossible to ensure high quality of light with this type of driver.

AC/driver-less LEDs

The third option is to use so called AC or driver-less LEDs. These solutions offer superior performance in terms of miniaturization. In many ways these solutions can be seen as a step further than the single stage solutions. These circuits do not include a converter as the previous solutions, but a circuit that controls the direction of the current. When the mains voltage is low, the current will be directed through a low number of LEDs and when the voltage increases so will the number of LEDs which the current is guided through. This gives a high power factor but creates a huge flicker problem. As for the single stage solutions. a big capacitor can be used on the output to reduce some of the flicker, but it brings the same challenges and add the challenges that the heat sensitive capacitor is now placed right next to the hot LEDs. Furthermore, some of the drivers have 100% light modulation (see following section) when dimming is utilized and all of them will exhibit this if phase cut dimming is used.

Flicker

All the solutions for miniaturized driver mentioned above lead to increase flicker. This is important to notice as flicker may not only lead to visually unpleasing light, but can also cause eye strain, headaches, be distracting and in some cases trigger medical conditions.

In order to ensure high quality of light and low flicker in a given installation, it is important to know how to specify and test for flicker. The most common specification of flicker still is a percent flicker (or modulation depth) given by (Figure 4):

$$\text{Percent Flicker} = 100\% \times \frac{(\max - \min)}{(\max + \min)} \quad (1)$$

Often the data sheet distinguishes between low frequency (HF; < 120 Hz) and high frequency (LF) flicker, but otherwise this a very simple and

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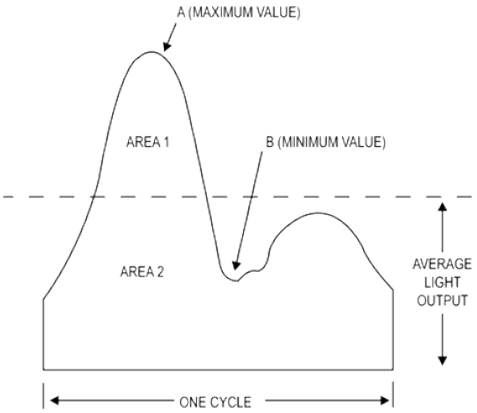

Figure 4: Percent Flicker [4].

also too simple way to ensure that a given driver will provide high quality of light.

In 2015 IEEE introduced a new standard for flicker, IEEE1789. This is not a requirement, but a recommendation. The new standard takes into account the fact that humans are less susceptible to flicker at higher frequencies. The standard specifies a recommended modulation depth for all frequencies up to 2.5 kHz. A few driver manufactures have taken on this standard and started to specify flicker according to this standard in their data sheet. Results of a market survey where drivers on the market have been tested according to the IEEE1789 can be seen in [3].

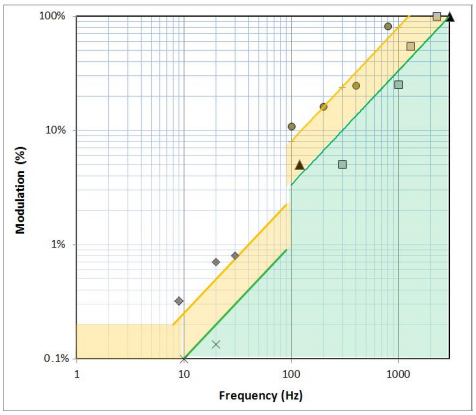

Figure 5: IEEE 1789 flicker recommendation [2].

While IEEE1789 provides way more information than the simple percent flicker, many argue that this is still insufficient to describe both flicker and stroboscopic effects.

Another way is to measure the low frequency flicker (< 80 Hz) based on the IEC PST or Flicker Visibility Measure (FVM) and the high frequency (80–2.5 kHz) stroboscopic effects based on the Stroboscopic Visibility Measure (SVM) method [4]. Both the FVM and SVM takes the waveforms of the flicker into account and targets a value below 1 as an acceptable level. The equation for both FVM and SVM is shown below, they are however summed over different frequency ranges and n is 2.05 for FVM and 3.7 for SVM. The values for n are based on human trials where the threshold for perceived flicker and stroboscopic effects have been tested.

$$\mathrm{FVM} = \mathrm{SVM} = \left(\sum_{m=1}^{\infty} \left| \frac{C_m}{T_m} \right|^n \right)^{\frac{1}{n}} \qquad (2)$$

with $<$ not visible, = just visible, $>$ 1 visible.

Unrecognized flicker effect: Beating

Today, lighting installations show a so far unrecognized flicker effect. This effect occurs in installations consisting either of several luminaires or luminaires which provide tunable white light. In the first case flicker is generated in spatial zones which are illuminated by different luminaires and in the second case flicker is generated because different light sources within one luminaires are controlled independently and thus non-synchronised.

Due to the superimposition of light which is generated by two or more separate control channels, a wave interference (=beating) is created. This effect is perceivable at low flicker frequencies. Limiting the frequency by which single LED sources are controlled is not relevant for this beating effect, since the effect is generated by frequency differences either in different light channels or in different luminaires.

The effect can be found in almost every lighting installation which consists of a number of luminaires with overlapping light beams or tunable white light luminaires. Miniaturization of luminaires is further aggravating this effect, because lighting designs typically consist of overlapping light beams. The described beating effect is demonstrated at booth C20, where it can be experienced visually, acoustically and metrologically.

Beating and its consequences can be detected in different scenarios:

- walls and stationary objects in the visual periphery are perceived as beating,

- rotating direction of objects seems to change spontaneously,
- estimation of the speed of moving objects becomes difficult and
- objects seem to change their colors.

These effects significantly affect visual perception and thus work performance. Furthermore, it may impair our well-being or even cause health problems (i.e., one out of 4000 people suffers from photosensitive epilepsy and thus is very sensitive to flicker frequencies between 1 to 70 Hz; flickering lights induce convulsions even within short exposure periods). This beating effect can hardly be controlled with better technical solutions. Although, this effect can be eliminated within one luminaire (e.g., by de-synchronizing flicker frequencies of different light channels), various external influencing factors, mainly caused by the lighting design, must be considered:

- spatial overlap of light beams of different luminaires
- different drivers are connected to different mains phases,
- different luminaires are exposed to different ambient temperatures,
- different luminaires have different dimming states and thus are operated for different time spans, which results in differently aged drivers, and
- luminaires from different manufacturers, containing different drivers, are installed.

Consequently, the lighting designer and the luminaire manufacturer have to work closely together to minimize this beating effect. To support this cooperation, technical solutions as well as lighting design guidelines are needed. Unfortunately, published recommendations do not consider this topic yet because they only consider flicker effects generated by single channel light control.

Miniaturized driver with high quality of light

In order to enable miniaturization while keeping high quality of light, Nordic Power Converters (NPC) have developed a new technology enabling LED drivers to operate at very high frequencies.

The volume and cost of drivers are mainly governed by passive energy storing elements (inductors and capacitors). They scale with the switching frequency and a dramatic increase in switching frequency will hence lead to highly increased power density and reduced cost. For hard-switched drivers this will however result in severe switching losses, which will ruin the efficiency and cause system failure.

By combining circuits from the RF industry with the design methodology of power electronics, new driver topologies have been designed, which eliminate these switching losses. This allows to increase switching frequencies and hence power density can be increased and costs can be reduced significantly.

The reduced need for passive energy storing elements allows the removal of heavy and bulky magnetic components and temperature sensitive electrolytic capacitors. Consequently, this measure increases the lifetime of the luminaire and thus allows a deeper integration of LEDs, LED drivers, heatsink into the luminaire.

In this way it is possible to significantly reduce the size of components used in the LED driver while keeping both, good mains performance and high quality of light. NPC is currently developing a new family of LED drivers based on this technology. The whole product family will consist of miniaturized LED drivers with high quality (flicker-free) light and good mains performance (Figure 6).

Figure 6: NPCs coming product family including fully in track drivers, AC/DCs for low voltage tracks, ultra slim isolated linear driver and compact tunable white drivers.

Need for further research

There exists a strong need to initiate psychophysiological studies to better understand visual, emotional and physiological disturbances generated by beating on human beings. This research should also aim at expanding current

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recommendations on flicker and stroboscopic effects and guide luminaire manufacturers and lighting designers to create lighting solutions without beating effects.

From a scientific perspective, investigating beating effects in tunable white light solutions is of particular interest, since an interaction of achromatic as well as chromatic beating effects are expected. In addition, this may become a hot topic in the near future, since the number of installed HCL solutions, containing tunable white lights, is steadily increasing and care must be taken to ensure that HCL lighting designs support the health and well-being of people all along the line.

Conclusions

LED lighting brings many new design opportunities and miniaturization have become a trend in the industry. It is desirable to make the lighting systems small enough to be integrated in the walls, ceilings and furnitures, leaving the room illuminated but the luminaires hidden. The driver has become a bottle neck in achieving further miniaturization and most drivers that address this topic, does so at the expense of the quality of light (flicker).

This problem increases two-fold when tunable white luminaires are used, the size of the driver increase and beating effects may appear due to superimposition of flicker on the two channels.

References

[1] IESNA Lighting Handbook, 9th edition (Rea 200)
[2] US Department of Energy, FLICKER: Understanding the New IEEE Recommended Practice. 2015.
[3] T.M. Anderson and M. Madsen, Latest Developments on Drivers — Control and Dimming. LpS 2018
[4] G. Perz, Temporal Quality of Light, CIE info day

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Lighting Requirements

544 Spectral Innovations in Theater Lighting
by Dipl. Ing. Markus Reisinger, Bühnenplanung Walter Kottke Ingenieure GmbH

548 A Call for Innovation – Can Entertainment Lighting Requirements be Combined in a Comprehensive Lighting Solution
by Dipl.-Wirtsch.-Ing. (BA) Ing. Christian Allabauer, OETHG - Österreichische Theatertechnische Gesellschaft

554 Modern Lighting Audits - Technology Supporting Designers and Contractors to Verify Lighting Installation Quality
by Miko Przybyla, GL OPTIC

Spectral Innovations in Theater Lighting

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Abstract

Color is an important factor for stage and theatre lighting designs. Multispectral light fixtures can satisfy both, the request for a large color gamut and the need for excellent light reproduction capabilities. Today we find in the market solutions with up to eight types of LEDs.

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Introduction

The inherent dynamics are among other reasons that make daylight a unique and attractive light source for humans. Changes in intensity, direction and spectral composition generate several positive effects. In architectural applications the spectrum is tuned with the aim to stimulate the organism, regulate the wake-asleep cycle and enrich perceptions through indicators for daytime, weather and season.

But light dynamics might also be used to establish unique spatial experiences and mark moments in time. These functions are highly important in the domain of stage and theatre lighting. The aim for theatre lighting is that visual appearance of the scene fits its emotional content. To achieve even more precise results than before new color mixing systems are commercially available. Multispectral LED sources are therein applied to master extreme subtle changes in color.

Multispectral LED lights

In the market we currently find products for stage and theatre that use up to 8 different types of LEDs. Some solutions enrich the spectrum by adding wide band emission spectra (e.g., lime) to small band chromatic colors. Resulting benefits are:

- Spectra suit specific camera requirements
- Optimize perceived color quality
- Very subtle variations in hue can be realized
- Lighting can be adapted to fit prevalent light

In cases were narrow emission bands are used a large extended color gamut is available.

One of the driving forces in developing multispectral fixtures have been the movie industries' request for excellent color reproduction. To verify the reproduction capabilities Le Gendre and colleagues evaluated multispectral systems with combinations of up to 11 LEDs. Responses for 28 camera types and a human observer were collected. They concluded that a combination of RGBW LEDs with a phosphor converted broadband amber LED as fifth component would satisfy the requirements [1].

The challenge with multispectral lights is that now intensities of five, six, seven or even eight types of LEDs needs control.

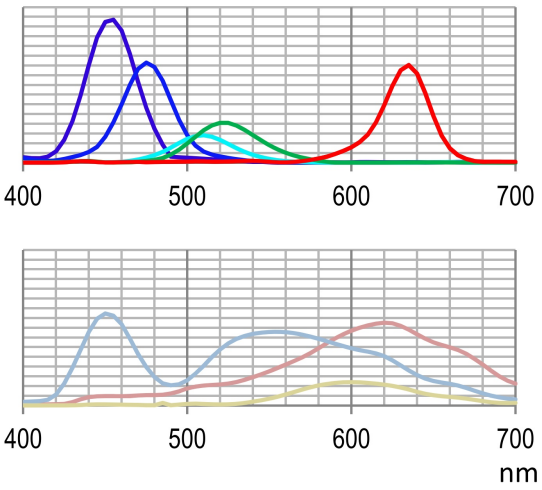

Figure 1: Emission spectrum of a wash light with 5 narrow band and 3 broad emitting LEDs.

Unlike RGB fixtures, there are basically infinite numbers of intensity combinations possible and hence to choose from. At the same time this is an opportunity to optimize spectra according certain criteria (aesthetics, health impact, energy consumption etc.). Interesting for stage applications are spectra that guide visual attention or increase emotional impact. To stimulate health effects or support biological rhythms might be the major achievements for other areas of application.

Future outlook

Now were industry embraced LED solutions with multispectral sources for theatre and entertainment we may expect more new developments. The days for lighting gels are definitely numbered. Beneficial for recent developments was that in theatre buildings lighting controls ever since were seamlessly integrated. While stage and theatre applications took a pioneering role in the future other application domains will benefit from usage of multispectral lights. Horticulture lighting already adapted colored lights. In retail environments customized spectra are used to optimize appearance of food and cloth. Multispectral fixtures designed for stage, film or theatre applications generally feature 16-bit dimming to enable smooth fades and precise color navigation. Some manufacturer are about to embed application knowledge to ease handling. This is for example the case when a separate DMX channel is added for green-magenta adjustments.

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Conclusions

Without any doubt LEDs paved the way to serve applications with custom designed light emission spectra. From fashion stores and stage applications now, evidences are available what can be achieved. In the future metameric mixtures of light may present us a whole new set of visual effects. In combination with surface colors these light mixtures bear the potential to generate astonishing effects. So far theatre is definitely the arena were possibilities of time modulated lights are explored.

References

[1] C. Le Gendre, Xueming Y. and Debevec P., Optimal LED Selection for Multispectral Lighting Reproduction, in ACM SIGGRAPH 2016 Posters, 72:1–72:2. SIGGRAPH '16. New York, NY, USA: ACM.

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A Call for Innovation – Can Entertainment Lighting Requirements be Combined in a Comprehensive Lighting Solution

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Abstract

The entertainment lighting sector is all about stage and studio lighting and raises significantly greater demands for tailored lighting solutions than most other sectors and general service lamps do. Currently there are no suitable replacements for natural (thermal) sources due to multiple reasons.

The basic thesis of this lecture is that synthetic light sources and high quality lighting do not contradict one another. The challenges we witness today and in the foreseeable future are largely caused by economic aspects and legislation that emphasises efficiency at the cost of lighting quality, except for a chosen few exceptions, where high lighting quality is crucial.

Even though there seems to be good arguments not to invest in research and development of high quality lighting solutions, there is a whole industry — with real purchasing power, that is demanding high quality lighting solutions. Additionally, other industries and the premium segment for even household lamps would benefit from returning to the unmatched quality of the simple “traditional” light bulb and while avoiding its disadvantages.

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Introduction

The EU spends a lot of effort on reducing overall energy consumption to achieve the climate goals of the Kyoto Agreement and to contribute to environmental sustainability. One measure to achieve this worthy goal is the regulation of luminous efficiency for various lighting sources. Current regulations already allow an exception for stage-, theatrical- and studio light sources, because of their unusual quality demands and singles out spectral distribution as a crucial criterion. There is an ongoing attempt to condense and simplify the three EU-directives relating to “EcoDesign” so that they can be replaced by a single directive that should come into force by September 2020. The draft presented at the EcoDesign Consultation Forum in December 2017 no longer highlighted stage lighting as an exception. The first public review finished in January 2018 gave rise to comments from various interest groups, theatrical associations, lighting designers, end-users, manufacturer associations who pointed out that there are currently no suitable replacements available on the market for tungsten lamps, that can fulfil all relevant theatrical lighting requirements. The European Commission invited the representatives of the sector to a meeting in Brussels and encouraged them to provide a recommendation for a technical solution for the entertainment lighting sector, while considering the need to close legal loopholes and feasibility of market surveillance. There is productive discussion going on and the results will be made public by the European Commission later in 2018.

The aim of this talk is to point out the special demands of theatrical lighting in plain language and pictures, outlining the special challenges in this particular industry to fulfil the highest artistic and technical requirements. The goal is to encourage manufacturers to develop and provide suitable technical alternatives. These solutions should preferably be realised at competitive prices, so as to be affordable for smaller installations as well.

Light — Definitions and Approaches

Light is the section of electromagnetic radiation — in the wavelength range of 380 and 780 nm [1] — that is visible to the human eye. Amazingly enough Wikipedia mentions a variation in the definitions greater than 100 nm (!) at either end.[1]

Figure 1: Visual spectrum in the electromagnet spectrum.[2]

Photometric units — like Lumen, Candela, Lux, nit — are based on radiometric units and weighted according to the brightness impression of the human eye. The Luminosity function describes the average visual perception of brightness in correlation to the wavelength. It is the link between radiometric (energetic, physical) and photometric (weighted by the standardized human eye, biological). The peak value is achieved at 555 nm. Human beings have a much lower sensitivity for light at the edges of the visual spectrum.

“Light is produced by one of two methods. . .

Incandescence is the emission of light from “hot” matter ($T \gtrsim 800$ K).

Luminescence is the emission of light when excited electrons fall to lower energy levels (in matter that may or may not be “hot”).” [2]

Challenges on the rejection of the thermo-photometric principle

Sun light, candle light, tungsten light, are all based on the black body radiation. Heating a piece of metal will result in visual radiation (light) from proximately 500 °C upwards. Theatrical tungsten lamps operate at proximately 3000 K. Sunlight has a colour temperature of 5500 K. So colour temperature reflects the actual temperature in Kelvin of a so called black body, which could be a piece of metal, heated to below the melting point, like a tungsten filament.

Small temperature difference

Assuming an ambient temperature of 30 °C and operating temperature for a LED should not exceed 80 °C to avoid colour drift over time

[1] See `https://en.wikipedia.org/wiki/Light`, last access 21.06.2018.

[2] Fig. 1 graphics based on a measurement with UPRtek’s CV600 Spectral Color Meter.

resulting temperature difference for LED is 50 K instead 2700 K for tungsten.

$$R_{\mathrm{Th}} = \frac{\Delta T}{P} \qquad (1)$$

According to the equation (1) a low thermal resistance is required to allow high power and therefore high intensity light light sources. To achieve this low thermal resistance extensive measures have to be taken, that use to result in sizeable heat sinks and fans.

Challenge: additional weight, size, costs, fan noise.

No thermal inertia (dimming, flickering)

Theatrical incandescent lamps are base on a piece of metal (typically tungsten filament) heated to 3000 K by high current density (magnitude 500 A/mm^2). Corresponding to the high temperature the thermal inertia is sufficient to create the impression of constant luminous flux to the human eye or cameras, easily tolerating phase control dimming on 50 Hz mains voltage.[3]

LEDs generate light output by luminescence. Luminescence does not imply thermal inertia. It responds instantly to voltage/current variations. That is one main reason why retrofit light bulbs can not dim down to zero intensity smoothly, but are rather flickering or switching ofin the lower area. Hence Professional LED spotlight typically work with PWM — pulse width modulation — using (variable) control frequencies $\geq$ 1000 Hz.

Challenge: demand for sophisticated and costly electronics.

Form factor and beam control

Optical systems consisting of mirrors, lenses can easily be optimized for punctuate light sources. Incandescent filaments are near enough to dot-shape to allow accurate beam control.

High output LED sources (no matter if single chip or arrays) typically have diameters above 5 cm which is not at all punctuate. Condensing optics reduce efficiency, but still do not approach the required quality of beam control for all applications. It is an accepted expression in lighting design: “It is much more difficult to get an area of the stage dark, than to get it bright!”

Challenge: beam control, avoid flare light.

No redshift

Incandescent lamps reduce their colour temperature when dimmed, according to black body curve. LEDs do not adopt on intensity changes. While this could be seen as an advantage for some technical applications, in stage lighting this is an intended and requested behaviour.

The simulate the redshift, some kind of colour mixing system is required, as well as adequate controls.

Challenge: colour mixing system and controls.

Spectral Distribution as a benchmark for lighting quality

Incandescent light sources are known for their continuous spectrum.

The highest intensity (λ_{peak}) is achieved at approx. 800 nm wavelength, with smooth surge and decrease.

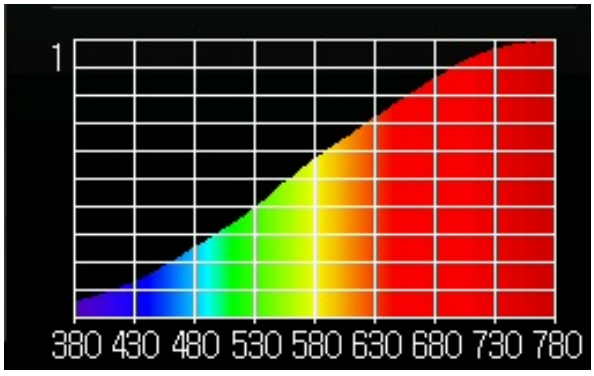

Figure 2: Spectral distribution of tungsten light source.[4]

LED light sources are known for their band spectrum. The source of radiation has narrow band of wavelengths with λ_{peak} around 450 nm. To

[3] Actually it is 100 Hz, due to positive and negative half cycle.

[4] Fig. 2 measurement with UPRtek’s CV600 Spectral Color Meter.

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achieve white light, phosphor (collective term for phosphorescence materials) is applied in front of the source of radiation. It converts parts of the "blue" radiation in "yellow" radiation, which is the complementary colour. Even though the result light is perceived as white, some parts of the visible spectrum are missing. The pathway of the spectrum is inconsistent and "rippled".

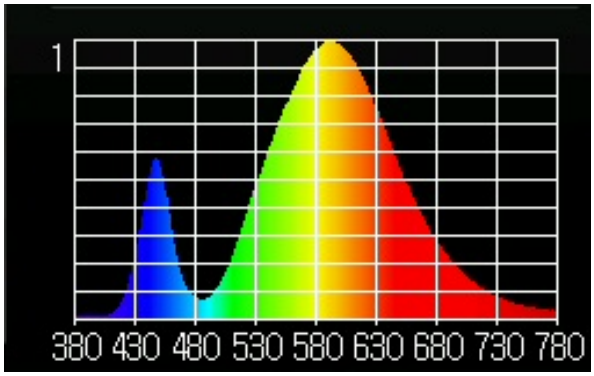

Figure 3: Spectral distribution of typical theatrical LED spotlight.[5]

CRI — colour rendering index — was not intended to describe the quality of LED sources, as it was defined ways before present-day LEDs were known and is replaced by other indexes, like TLCI for studio applications, to allow accurate colour rendering evaluation.

So called "high CRI" light source tend to reduce the drop between the "blue" and "yellow" peak. Even though they lack coverage of the borders of the visible spectrum and often show an uneven progression.

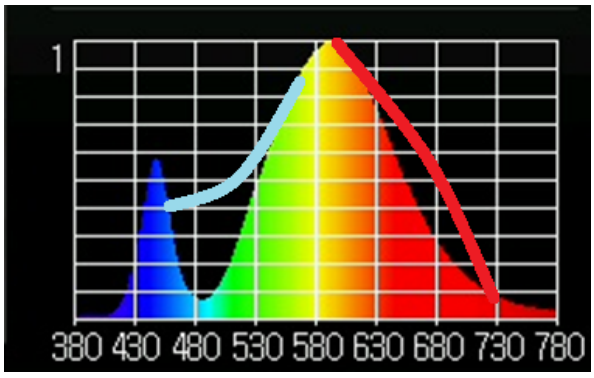

Figure 4: Spectral distribution "of high CRI" theatrical LED spotlight.[6]

[5]Fig. 3 measurement with UPRtek's CV600 Spectral Color Meter.

[6]Fig. 4 graphics based on a measurement with UPRtek's CV600 Spectral Color Meter.

Lighting Design Aspects

There are various aspects to Light Design. These are related to the situation the design shall apply to.

Light Design starts whenwhen a situation is simply being illuminated. Depending on the 'type of eye' looking at the situation, human or camera, the scenario needs to be balanced in brightness and colour temperature to enable the 'eye' getting the right picture. Such a situation tries to imitate daylight as this what our human eye is made for.

Daylight can be defined in terms of characteristics and colour temperature. For the camera we already have to adjust related to the ability of the camera, finally the screen showing the recorded scenario defines how the lights have to be set.

Beside this generic Light Design, where 'right' could be defined as the moment where the scenario is well presented and 'wrong' would mean, it's hard to get the visual details of the illuminated object or scenario, there are also several other Light Design applications.

Theatre, Movie, Concerts, Urban Lighting as examples of creative architectural Light Design require more creative ways of setting light. In most of these applications right or wrong is a matter of artistic creativity and/or opinion.

Theatre, film and concerts lighting design needs to support the emotions of the scene or song. They need to put the actor or musician into the 'right light'. And although it's not always required to get a detailed view, the scene is like a picture which needs to be supported by the way the lights are set. Colours and colour temperature can be adjusted while proper CRI can be ignored. This should not detract from the necessity of having good CRI: the better the lighting fixture, the better we can work with it. Drawing pictures with lights will always use any available light sources, starting with the use of a generic 'forbidden' bulb and still doesn't end with using multifunctional moving lights or projectors.

Urban Lighting or Architectural Light Design nowadays tries to make a building visible while the surroundings of the building remain dark — in theory. In general, architectural lighting has two categories. Illuminating the used areas of the building in a proper way is always done. Most times by a simple calculation to meet the

requested need of illumination for office or business applications. In many cases visual appearance is ignored.

The other category is presenting the building against a skyline. This starts by simply illuminating the facade, and can extend to turning the building into a screen with lower or higher resolution. Depending on the location of the building, illuminating the environment is an important aspect for getting the permission to do so. In some cases, the type of content played on the building is limited to certain times a day.

Conclusions

There are existing LED solutions providing smooth dimming, including redshift at the quality-level of existing tungsten solutions. The economic challenge is to provide this technically more complex solutions at an reasonable price.

Incandescent light sources are perfect light sources to the human eye, as they cover the entire visible spectrum, but a considerable amount of its radiation is outside of the visible spectrum, also known as infra red. Energy savings are to be achieved by covering the visible spectrum only. Even thought energy savings must not be achieved by getting rid of parts of the visible spectrum or an imbalanced distribution within the spectrum, as this falsifies and cuts artistic means of expression.

Basic LED sources only cover parts of the visible spectrum. Additional types of phosphor or more different saturated colour LEDs add more wavelengths. Products available on the market do not provide smooth, continuous spectral distribution thought. Especially at the borders of the visible spectrum there are no suitable replacements in the market to cover the variety of required lighting instruments.

The technical challenges to create high output LED light sources to cover most theatrical lighting application are to provide continuous full spectrum (380–780 nm) light sources, that are near enough to dot-size to provide exact beam control, without disturbing noise.

(Entertainment) Lighting Design is a crucial artistic means of expression to support emotional reactions of the audience and help creating the very special moments of a live event. To achieve this aims it is vital to provide a variety of full spectrum instruments to lighting artists.

References

[1] Hans-Jürgen Hentschel, Licht und Beleuchtung, Heidelberg: Huethig Buch Verlag, 1994, ch. 4.

[2] https://physics.info/light/lastaccess21.06.2018

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Modern Lighting Audits - Technology Supporting Designers and Contractors to Verify Lighting Installation Quality

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Abstract

LED products quality assurance has been discussed a lot in the last several years. Many standards and system solutions were developed to control the lighting product quality. Lamp manufacturers and end-users has been usually focusing on better product performance, efficacy and product compliance.

This paper provides a detailed description of a novel solution which combines the CAD lighting design software with the on-site measurement supported by new technology illuminance spectroradiometers able to handle measurement procedure applied to verify and report lighting levels and other quality measures using CAD plans as a reference and reporting illuminance level back to the design software.

It also discusses the use of Imaging Luminance Measurement Devices in the practical verification of luminance levels inside and outside buildings. Available design tools support designers with calculation and simulation of luminance levels but little is available when the onsite software and hardware tools are available for onsite verification. This is especially critical for verification of architectural and road lighting installation.

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Motivation

Citius, Altius, Fortius, which is Latin for "Faster, Higher, Stronger". An Olympic slogan could easily be adopted to the modern LED lighting industry race that we are all observing nowadays. This market is moving very fast and almost every member of this industry is trying to deliver faster, better and more reliable products. At the same time with the increasing number of technical possibilities and expanding knowledge about the influence of light we struggle to tell the good from bad and make right decision regarding the selection of components and choosing the right products.

LED products quality assurance has been discussed a lot in the last several years. Many standards and system solutions were developed to control the lighting product quality. Lamp manufacturers and end-users have been usually focusing on better product performance, efficacy and product compliance.

However nowadays companies working to WELL Building Standard or those in need for California Title 24 standard compliance struggle with onsite lighting quality evaluation. This is primarily caused by the extended scope of new metrics and measurements needed for the verification of the quality of a complete light installation. There is also a huge gap between the Computer Aided Design software world and a real life lighting installation. Therefore, a growing need for dependable and practical on-site LED lighting verification has recently been observed.

Old Standards, New Metrics

Traditional approach for on-site lighting audits was focused on photometric quantities like illuminance or luminance. These are the two most important values for onsite lighting installation evaluation. They are included in a majority of lighting standards around the world as well. Therefore, lighting designers and lighting companies use these quantities at the design stage and also as a verification metrics when they deliver lighting solutions.

It should be noted that the above mentioned values are only based on a photometric approach providing information about the amount of light in a quantitative manner. Due to the fact that our knowledge about the influence of light onto the human body and performance is increasing and the technology is able to support the effective use of lighting to increase the well-being of people. There is a need for software solutions and measurement instrumentation tools for which could help in the verification of lighting quality.

Generally available CAD based lighting design software uses photometric data and is not able to handle other qualities beside the colour temperature that one can specify for the project as general information. Despite this, the good practices used by some designers and manufacturers aiming at delivering better lighting systems, superior to competitor products, are ready to verify additional quality measures to check the quality and prove the advantages of the solution they deliver. Approved new metrics which are valid for lighting product verification and which are commonly used for lighting audits purposes are available. They have not yet been agreed by standardization organizations as part of lighting audits requirements. These are newly approved rendering indices according to IES TM-30, Spectral Analysis as a basis for effective lighting verification, Equivalent melanopic lux (EML) suggested by LRC and used by WELL Building Standard to verify circadian lighting and all different flicker parameters which can be measured too at present as additional quantifiers.

Table 1: Traditional Light Quality Metrics vs. Modern.

Traditional Photometric Approach	Modern Comprehensive Approach
Illumination lx	Spectral Power Distribution
Spot Luminance cd/m2	Colour
	Colour Rendering
	Effective illumination values: EML Equivalent Melanopic Lux MP Ratio PAR/ PPFD
	TLA - light flicker

The traditional approach was focused around photometric values and traditional photometers were suitable to perform the lighting audit. Usually lux meters were, and still are, used for illumination i.e., lux level verification. And for luminance measurement simple spot luminance meters with a fixed field of view were used.

The new augmented approach to light quality verification though requires the use of more advanced instruments, light spectral illuminance meters and imaging luminance meters which can be connected to a software interface and which are able to provide more information about the light quality beside information about the quantity.

There are two major obstacles slowing down common use of the new approach in lighting audits and these are: the accessibility of the instruments able to perform such evaluation and the fact that these new metrics are not yet the part of international standards. The industry and organizations such as Lighting Research Centre (LRC) or WELL are moving towards the more advanced lighting verification and put additional, newly proposed metrics as criteria to verify the conformance of lighting installations. At the same time official mandatory regulations based on standards do not cover these new factors at all.

The accessibility issue can be explained by the instrument pricing because in order to perform an onsite measurement that covers additional metrics there is a need for a reliable spectroradiometer which is obviously more expensive than a standard lux meters commonly used on a building site. This is why these instruments are not yet accessible for everyone in the industry. Another issue is that despite the fact that there are a number of portable spectrometers available on the market, not many are properly calibrated or accurate enough for these more advanced applications and not all of them are able to calculate new values.

New concept for the illuminance lighting audits

Every lighting installation should be verified before it is commissioned. This requirement, depending on the lighting installation and its location, is either mandatory by law or required by the contract. The new concept for modern lighting audits was particularly triggered by the requirements developed by large lighting companies. They are in need for practical instruments which can use the digital data they have available from the CAD design software which is generating the measurement grid layer with designed illumination levels. The concept was to use this data as reference values and provide the software and hardware solution to be able to verify the existing lighting levels onsite. The process should support the auditing person in the measurements and also allow for the preparation of a comprehensive report.

The R and D team of GL Optic assigned software and hardware engineers to develop a solution to close the gap between the available sophisticated CAD design tools and a real life installations.

The objectives of the project were as follows:

- Single instrument to measure lux and other parameters
- Interface to communicate with CAD design software to obtain reference data
- Firmware supporting the onsite measurements process
- Reporting tools to compare the measured values with the designed lighting levels

Figure 1: Spectroradiometer with flicker measuring module.

For the purpose of this development only the lux values verification was considered. Nevertheless, each measurement data file incorporates additional spectral characterization which can be used for colour and active radiation verification for specific application like human centric lighting metrics or light flicker evaluation. This concept has been designed and evaluated with the use the DIALux software where the lighting design was made.

The principle is as follows:

- Lighting design is made in DIALux and the measurement grid including the designed

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illumination levels is exported to the CAD software as a layer.
- This layer is then imported to the GL Spectrosoft where the selected points for the verification are marked to create the list of points for the onsite verification.
- The list is uploaded to the measurement device the GL SPECTIS 1.0Touch + Flicker
- Now the lighting audit can be made on-site and the subsequent measurements are made point by point with the device and the operator can observe on the screen the actual measured point number and can locate this on the general plan.
- Once the measurements are made the list including the measured values can be imported to CAD software as an additional layer.
- The measured values are displayed next to the design values, which simplifies verification and supports comprehensive report preparation.

This solution helps to avoid tedious measurements made with portable meter and making manual notes of lux values which then need to be reported somehow to the customer or contractor. Performing the lighting audit with prepared points displayed onboard the measuring device significantly supports large building audits where hundreds of points need to be verified and a lot of data can be analyzed.

New concept for luminance lighting audits

Luminance distribution is another challenge for engineers performing onsite lighting audits and it is the most important quantity in lighting design and the most important measure in road design and architectural illumination. LEDs are very bright light sources, which are characterized by high light efficacy. Unfortunately, the annoying effect of glare is a specific side-effect of LED construction. The assessment of glare is dependent on the luminance value in relation to the background luminance level. Designers and lighting companies often use design software and the available visualisation functions for lighting installations, where luminance plays a key role. However, there is a big discrepancy between the assumptions of the designer and the design and the actual implementation of the lighting system. As the technological possibilities of LED luminaire construction and lighting control increase, the need for more reliable verification of lighting quality at the stage of completion of construction works increases. The client, the customer or the contracting authority more and more often demand a report and a declaration of conformity of the installation with the design and the order.

Figure 2: Imaging Luminance Measuring Device.

Traditional luminance meters using a single lens optical system and appropriately adjusted photodiode, the so-called spot luminance meters, allowed for precise targeting and precise focusing at a small point. They are fast and reliable, but have two main disadvantages due to their technical characteristics. Firstly, they usually have a very small angle of view, i.e., from a given distance we can measure an area (point) with relatively small dimensions, which in the case of luminance distribution measurements forces the user to make multiple measurements and calculate the luminance distribution of a given area manually. Secondly, the matching class of a photodiode with a V-filter (lambda) may cause more or fewer measurement errors depending on the type of light source or the colour temperature. These meters were perfect for measurements of light sources with a wide range of radiation. On the other hand, in the case of some white LED sources, especially RGB systems, the errors can be up to 20 percent for a good class meter.

New solutions available on the market, using CMOS or CCD sensor technology, commonly used in digital cameras, offer far greater possibilities to use this technology both for measuring and testing the luminance of illuminated surfaces, as well as illuminated

elements and the luminaires and light sources. With the use of a camera luminance measurement system, the so-called Imaging Luminance Measuring Device (ILMD), it is possible to perform measurements and compare luminance values on the basis of the image analysis.

These meters are equipped with a high-resolution sensor and optical system consisting of a lens and a V (lambda) filter adjusting the sensitivity of the sensor to the sensitivity of the human eye. In this way, the image recorded by the sensor is subject to computer analysis, and the recorded brightness level corresponds to the impression received by the human eye, i.e., it is the level of absolute luminance value. In contrast to an ordinary camera, where the level of brightness in different places of the image is a relative value, in the case of a luminance matrix meter we have an image showing the distribution of luminance, and on its basis we can analyse, compare and measure the level, uniformity, changes in values, etc., for each point individually or for a given area of the image.

Thanks to this technology, with the use of a matrix with several million pixels, we can record the entire image of a given surface, a lighting element or the entire interior of a building. The recorded images can be analysed in detail with the supplied software. With image analysis tools it is possible to quickly mark the fields or points of interest and easily assess, both visually and metrologically, the connections between different measurement areas. Dedicated software for such matrix systems allows for additional presentation of levels in pseudo-colours, isocandels, 3D charts, in the form of histograms, to create reports and contains many other useful functions.

When it is necessary to determine luminance coefficients throughout the scene, a traditional, point-based meter seems to be an uncomfortable solution. Point by point measurements would have to be made, which would be very time-consuming and would not be applied in practice. Similarly, the measurement of small parts cannot be carried out with such a luminance meter because the measuring angle is constant and usually not small enough. The method with an ILMD meter compared to a spot meter allows for a wider view of the scene. All the luminance information in the frame can be stored in a single image, so this method takes much less time.

Repeatability is also an important advantage compared to a point by point measurement of luminance, as the measured image can be recorded and re-assessed at a later date. Problems with filter mismatch and possible correction of indications for different types of light sources or colour temperature can be solved by combining a matrix system with a spectroradiometric system. This increases the accuracy of the luminance measurement and additionally allows for colorimetric analysis, e.g., of colour temperature, colour rendering index. In advanced systems, this is part of a complex measuring instrument. It is also possible to use a two-stage measurement for this purpose, where we first measure the luminance with an ILMD meter, and then we measure the spectral distribution of the lighting with a spectroradiometer. So with this software it is possible to combine measurement data and present consistent reports.

Conclusions

As the new metrics are introduced, more and more widely available and also cheaper measuring instruments and new software give hope that reliable measurements of lighting installations will improve the quality of lighting while reducing energy consumption. The future of lighting quality control system should provide a practical assistance to lighting industry as the comprehensive lighting evaluation is becoming a necessity for every day application and is no longer limited to a laboratory environment. In qualitative terms, we should be providing light where it is necessary, as much as is necessary and whenever it is needed.

References

[1] Veitch JA. Commentary: On unanswered questions. Proceedings of the First CIE Symposium on Lighting Quality. Vienna, Austria: CIE; 1998. CIE x015:1998: 88.

[2] CIE TN 006:2016 Visual Aspects of Time-Modulated Lighting Systems.

[3] Rea et. al. Circadian Light, Circadian Stimulus, J Circadian Rhythms. 2010.

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Workshops

562 Solid-State Lighting Measurements
by Dr. Denan Konjhodzic, Instrument Systems

Solid-State Lighting Measurements

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Abstract

The important basics for measurements of solid-state lighting (SSL) products will be summarized in this paper. The focus lies on integrating spheres and goniophotometers, both as turning detector and turning luminaire. Since CIE S025 is the first international standard on requirements to perform photometric and colorimetric measurements on SSL devices the content and consequences of CIE S025 will be reviewed in most important details. To provide further application insight to SSL measurement a comparative study of the previously introduced methods will be presented. Particularly, an implementation of the auxiliary photometer method for goniophotometric measurements recommended by CIE S025 will be briefly presented.

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Introduction

The lighting industry has developed many new products based on white LED sources in recent years. These products are grouped under the term SSL (solid state lighting) light sources and consist of two- or three-dimensional ordered or non-ordered arrays of LEDs, which already contain all the necessary electronic components and heat sinks. The correct optical and photometric characterization of SSL light sources is a challenge, especially since there was no international standard available for a long time. CIE S025 [1] represents a milestone as the first international standard for the analysis and presentation of photometric data from SSL sources and it has replaced previously wide used North American LM-79 [2]. Both standards recommend the measurement of absolute total luminous flux Φ_v of the SSL-based luminaires, which can be carried out either with an integrating sphere or a goniophotometer. Both can be used in combination with a spectroradiometer, which allows all other photometric and colorimetric quantities such as 'correlated colour temperature' (CCT) and 'colour rendering index' (CRI) to be measured at the same time. CIE S025 defines uniform standard test conditions, as well as special requirements and instrumentation. Each standard test condition is subject to a set value and a tolerance condition which is specified by a tolerance interval. Since the definition of the tolerance interval does not take account of measurement uncertainty, the range yielded by deduction of the uncertainty is known as the acceptance interval. The measured parameter must be within the acceptance interval or be corrected for a standard-compliant measurement.

Measurements in an integrating sphere

For the fast measurement of luminous flux of SSL light sources and their further optical characterization (CCT, CRI, ...), an integrating sphere with a spectroradiometer is the recommended instrument. An ideal integrating sphere is an empty hollow sphere without absorbing surfaces, whose inner surface is coated with a perfectly diffuse reflecting material. Through many internal reflections the light is then uniformly distributed in the entire sphere, spatially and spectrally, regardless of the initial radiation pattern of the light source. In an ideal integrating sphere the irradiance can be measured at any point as a measure for the luminous flux of the source. The measuring system can be easily calibrated for the direct measurement of luminous flux.

For a real sphere, there are some technical limitations, such as the aging of the coating, the geometry of the baffles and the sample holder, as well as the effect of near-field reflection and self-absorption. Since the measured light source is from the perspective of the integrating sphere a source of interference itself, with its own absorption, it is necessary to perform self-absorption correction using a suitable auxiliary lamp prior to measurement (Figure 2).

Figure 1: Integrating sphere with 2 m diameter ideal for solid-state lighting measurements.

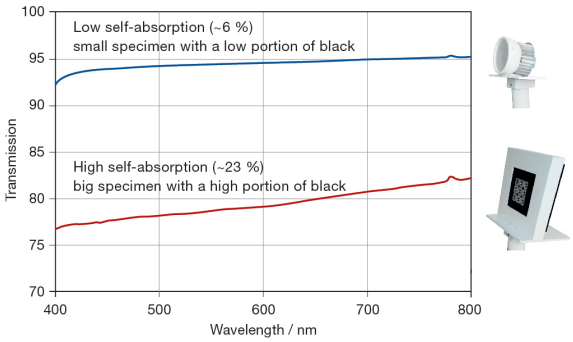

Figure 2: Examples for self-absorption spectra.

Measurements with a goniophotometer

Goniophotometers are normally used for the determination of illuminance and luminous intensity distributions. They are also applied for measurements of the total luminous flux by appropriate numerical integration of these

distributions. Although determining the luminous flux with a goniophotometer is much more time-consuming by comparison with measurement in an integrating sphere, it is significantly more accurate.

This method adds up the measured values for illuminance in all the angle positions around a light source. This approach is preferred by leading national laboratories which provide reference values for other measurement procedures. A goniophotometer is absolutely essential if parameters like partial luminous flux or beam angle are to be determined for light sources, as is the case in characterization for energy efficiency [3]. The goniophotometer unit can be used with both a conventional photometer and a spectroradiometer depending on the test objective.

Using a photometer head as a detector allows very fast measurements to be carried out for luminous flux and luminous intensity distribution. The photometer must have good adjustment to the sensitivity function of the human eye V(λ) in order to measure SSL light sources. The general V(λ) mismatch index f_1' is normally used to represent this property. f_1' must be less than or equal to 3% in order to carry out measurements in conformity with the standard [1].

If a spectroradiometer is used instead of the photometer, the system is known as a goniospectroradiometer. It allows the spatial distribution to be measured for all relevant photometric and colorimetric parameters. A high color rendering index is an increasingly important criterion impacting on decision-making when developing and marketing LED light sources. Goniospectroradiometry is therefore a universally important tool for defining all the characteristics of SSL light sources. Furthermore, SSL light sources with narrowband spectral components can be measured with a significantly higher level of accuracy. The spectroradiometer must cover at least the wavelength range of 380 to 780 nm with a wavelength accuracy of less than 0.5 nm and a maximum bandwidth of 5 nm [1]. It is even better if the entire visible spectrum of 360 to 830 nm [4] is covered.

The LM-79 recommended measuring the device under test (DUT) in the operating orientation in order to mitigate potential differences in convective cooling, although the burning position of individual LEDs is actually irrelevant in SSL light sources. The new standard CIE S025 relaxes this restriction and specifies the tolerance condition that the device under test needs to remain continuously in its specified burning position during the stabilization and test period [1]. If this condition is not complied with, the measurements have to be corrected to match the behavior of the device under test, e.g., by using an auxiliary photometer method.

Turning detector goniophotometer - Luminous flux integrator

A so called luminous flux integrator can be used to characterize the DUT in the required burning position. This upgrade option of the turning luminaire goniophotometer has an integrator arm and a separate sample holder which convert the instrument to a goniometer with a rotating detector. This type of goniometer allows the device under test to remain in position unchanged and the detector moves on the surface of a sphere around the luminaire (Figure 3). The function of detector can be fulfilled either solely by a photometer head or with the additional use of an optical probe for a spectroradiometer. Both devices are located in a stray light tube which minimizes any undesired extraneous light during measurement. The distance between the detector and the luminaire is fixed and limited by the design, so that the condition for photometric limit range is only met for small sources. However, this is not necessary for determining the luminous flux by integration of the illuminance distribution. A maximum dimension of the source can be specified depending on its emission angle. This permits additional luminous intensity distributions and all photometric and colorimetric spatial radiation patterns in the far field.

Turning luminaire goniophotometer

Figure 4 shows a turning luminaire goniophotometer which uses a C,γ coordinate system in conformity with CIE 121-1996. The photometer head can be aligned on the optical axis of the device under test at any fixed distance along the C-axis of the goniophotometer. The distance of the measuring head should be selected so that it is at least 15 times the longest dimension of the source. This guarantees that the

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Figure 3: Turning detector goniophotometer - Luminous flux integrator.

Figure 4: Turning luminaire goniophotometer.

detector is always positioned in the far field of the luminaire in conformity with the most stringent requirement of CIE S025 for narrow-angled sources [1]. The photometer head is shielded by a tube against unwanted stray light. Alternatively, an optical probe for a spectrometer can be used as a detector.

The luminaire is rotated about the C- and the γ-axis of the goniometer, i.e., it changes its burning position during the measurement. It is important to ensure before every measurement that the luminaire is burned in appropriately in conformity with the specifications of LM-79 and CIE S025.

Burning position correction

If, as in the case of the turning luminaire goniometer, the operating position of the luminaire deviates during the measurement from its designed burning position, a correction of the measurement values is necessary in conformity with CIE S025 [1]. The measurement results have to be corrected to take account of the characteristic dependence of the burning position for the specific device under test and the actual burning position used. The deviation can be determined with an auxiliary photometer. In order to achieve this, the alignment and the distance of the photometer head to the light source may not be changed during the movement. This ensures that a change in luminous flux of the DUT, caused by changing the burning position, results in a proportional photocurrent. A correction factor is determined and applied for each position of the goniophotometer approached with reference to the photometer value in the standard burning position. Since the position correction can be carried out directly after the measurement with the turning luminaire goniometer, this avoids the long burn-in of the light source and the additional time required is reasonable. The standard allows a typical position correction to be used when testing a large number of similar types of light source. This also saves valuable measuring time.

Comparison results

Table 1 summarizes the results of the luminous flux measurements of various light sources carried out using the luminous flux integrator and

compares these with the results obtained by means of the turning luminaire goniometer. The results are very consistent particularly if you consider that different measuring systems with varying geometries and calibrations are involved. Since all measurement deviations are within typical measurement uncertainties for the individual systems, a dependence on the burning position cannot easily be concluded. Rather, a systematic measurement deviation of approximately 1% can be identified.

The measurement deviations of the turning luminaire goniometer are comparatively low with respect to the measured value of the luminous flux integrator, although the light sources are continually changing their burning position and the movement leads to cooling and may therefore exert an impact on results. The deviation is so low in particular for all the SSL downlights and an LED module with installed heat sink that a position correction does not appear to be necessary. It is not surprising that the rotation of the downlights about the C-axis during the measurement with the turning luminaire goniometer does not cause any change in the luminous flux because the fins on the heat sink are configured symmetrically around the luminaire. Active cooling in the LED module with a cooler is not position dependent, as expected. Even if the deviations are relatively low in a 30 W LED floodlight and a 300 W halogen lamp with a gas mixture which simulates the sun, a position correction can be applied here as described. The corrected luminous fluxes improve by comparison with the luminous flux integrator and the deviation is just 0.3% for the LED floodlight and −0.9% for the sun lamp. One reason for the slight position dependence of the LED floodlight could be the configuration of the cooling fins on the heat sink which are aligned in a parallel direction and may cause a slight variation in cooling behavior when being rotated at the turning luminaire goniometer. Light sources which provide position dependence can therefore also be measured very easily with the turning luminaire goniometer if subsequent position correction is used in conformity with CIE S025.

Conclusions

Goniospectroradiometry is a very powerful tool to characterise SSL light sources based on LEDs. While the goniophotometer provides faster measurements, only goniospectroradiometer allows spatial resolution of all photometric and colorimetric quantities such as CRI. The luminous flux is calculated by numerical integration of the goniometric scan results. If the luminous flux is the main interest and averaged colorimetric quantities sufficient, the use of an integrating sphere with a spectroradiometer is recommended for fast measurements.

Goniophotometric comparative measurements with a luminous flux integrator (constant operational burning position) and a turning luminaire goniometer (burning position changes during the measurement) may reveal, at most, minimal dependence on the operating position for the light sources investigated. Nevertheless, the possibility of a position correction using the auxiliary photometer method in conformity with CIE S025 was demonstrated. This allows measurements also to be carried out in conformity with the standard using a turning luminaire goniometer which has a compact footprint and is easy to operate.

References

[1] CIE S025:2015, Test Method for LED Lamps, LED Luminaires, and LED Modules, CIE Vienna, 2014.
[2] IES LM-79-08, Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products, 2008.
[3] Commission Regulation (EU) No. 1194/2012, Official Journal of the European Union L 342 dated 14.12.2012.
[4] CIE S014-1/E:2006, Colorimetry Part 1: CIE Standard Colorimetric Observers, CIE Vienna, 2006.

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Table 1: Comparison of the luminous flux measured with the luminous flux integrator and the turning luminaire goniophotometer for different light sources.

Light source	Emission angle	Luminous flux integrator Φ_v [lm]	Turning luminaire goniophotometer Φ_v [lm]	Deviation
SSL downlight 1	97°	798.0	806.9	1.1%
SSL downlight 2	80°	665.3	671.9	1.0%
SSL downlight 3	52°	1834	1878	2.4%
SSL downlight 4	29°	403.0	409.4	1.6%
LED module with cooler	104°	1167	1178	0.9%
LED floodlight	103°	1697	1743	2.7%
Sun lamp (halogen)	32°	4150	4021	−3.1%

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