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Review

LpR

The Global Information Hub for Lighting Technologies and Design

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From micro-LEDs to Integrative Lighting II

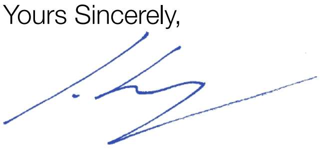
In this issue, we once again turn our attention to microLED technology. Professors LIN and JIANG from Texas Tech University discussed additional issues with us on this topic. The article on the development of microLEDs rounds off the microLED insights in terms of content.

The second focus is on integrative lighting and shows the influence and possibilities of spectrally optimized lighting from both the scientific and developmental sides. In the scientific part, the effects on our sleep are investigated, and in the practical part, approaches of spectral optimization by using particular multi-LED sources are presented. What the Good Light Group understands by good light is explained to us by Jan Denneman. Thomas Zampieri clarifies OSRAM's view on Modern HCL Designs in his commentary.

This issue also approaches the topic of sustainability from the perspective of control systems and their standardization in the DALI/D4i article by Paul Droshin. Lichtvision presents a futuristic lighting design project from China, the Changzhou Culture Plaza.

I hope you enjoy reading this issue as much as we did putting it together!

Yours Sincerely,



Siegfried Luger

Luger Research e.U., Founder & CEO
LED professional, Trends in Lighting, LpS Digital & Global Lighting Directory
International Solid-State Lighting Alliance (ISA), Member of the Board of Advisors
Member of the Good Light Group and the European Photonics Industry Consortium

More success for your horticulture projects with OSRAM LED technology

With Planta Seed, OSRAM DS brings highly efficient LED modules to market

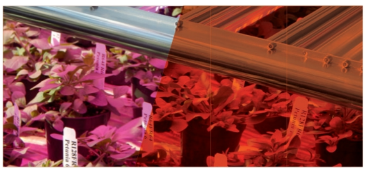
Horticulture is a fast-growing market. A key to successful production in greenhouses and vertical farming is the effective use of light. However, traditionally used high-pressure sodium (HPS) lamps consume a lot of energy and are not always able to provide the right spectrum when needed. Now is the time to switch to high-efficiency LED systems with optimized spectra.

With the innovative Planta Seed LED modules, OSRAM DS is launching future-proof and high-performance modules perfectly matching your horticulture lighting solution. Compatible with our LED drivers, Planta Seed LED modules are as flexible as they are customizable – perfect for your successful entry into horticulture.

Thanks to our unique expertise – system competence (LED chips, LED modules, LED drivers, and controls) – OSRAM DS has long since established itself as a strong partner for standard as well as customized lighting concepts in indoor farming. For efficient and modern horticulture solutions, OSRAM DS offers its customers not only excellent consulting service but also customization, including luminaire authorization.

Thanks to a photon-flux efficiency of up to 3.6 µmol/J, you can increase the growth rate of your plants and at the same time optimize your operating costs.

Compatible and expandable with our LED drivers, Planta Seed modules are as flexible as they are individually applicable. For example, combine PlantaSeed R90B10 or PlantaSeed R30W70 with OT FIT 380/220-240/1A4 D NFC HC L LED or further ingress-protected (IP) LED drivers for your toplighting greenhouse system.



In the CEA (controlled-environment agriculture) sector, horticulture is the fastest-growing market. Food can be produced year-round, locally and fresh – regardless of the seasons and environmental factors.

Traditional lighting with HPS can finally be replaced by energy-saving LED concepts. For the same amount of energy, 1,000 W LED luminaires provide more light output and an even better spectrum.

Contact our sales department at OSRAM Digital Systems and go online:
www.osram.com/linear

Rauno Pokall

Rauno Pokall is Senior Product Manager at OSRAM and expert for customization. He offers targeted solutions for the growing horticulture market, which has grown strongly in recent years.

Nicolai Heber

Nicolai Heber is Product Portfolio Manager of Linear Constant Current Systems. For 16 years, he has been in the Lighting Business, in various functions such as Sales, Business Development and Product Marketing.

The Planta Seed modules at a glance:

- In two different specific spectrum variants
- A reliable basis for most of the horticulture projects
- Future-proof systems thanks to Zhaga-Book-15-standardized LED modules
- Very high efficiency with up to 3.6 µmol/J for optimized operating costs and faster growth
- High reliability thanks to first-class light sources
- Possible system offers with matching LED drivers, e.g. OT FIT 380/220-240/1A4 D NFC HC L or IP-protected LED drivers
- Flexible for customization by type of spectrum

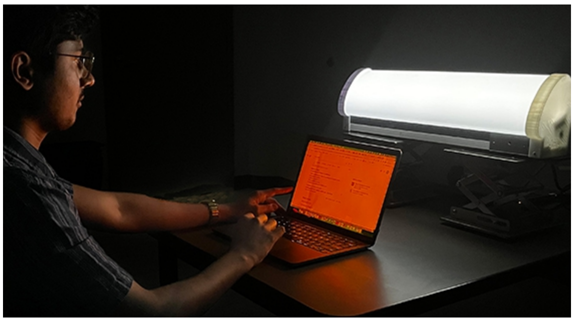
OSRAM. The light you need.

OSRAM Digital Systems delivers technology for successful LED projects. From components to complete systems, from individual solutions to large-scale installations. Whether in industry, at trade fairs, in parking garages or in retail stores – you can always rely on OSRAM quality components.

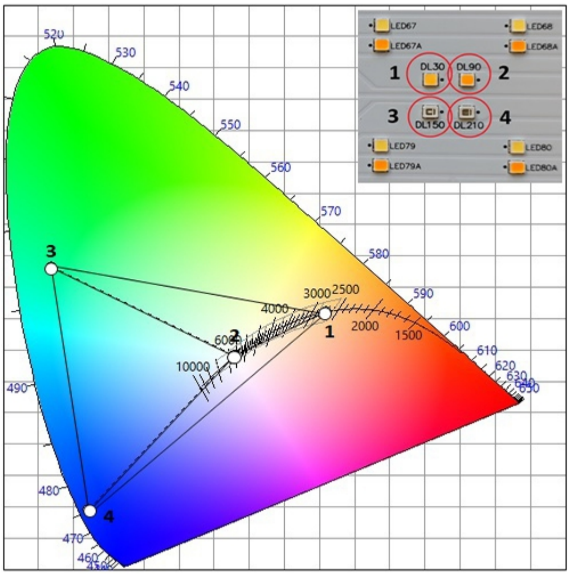
Light is OSRAM

OSRAM

HCL



SPECTRAL ADJUSTMENT TECHNOLOGIES



DALI

GOOD LIGHT

ADVERTISING INDEX

Thomas ZAMPIERI

Thomas is a Senior Product Marketing Manager at OSRAM Digital Systems and is based in Italy. With his expertise, he manages a comprehensive OSRAM portfolio in the field of constant voltage technology: Constant Voltage LED drivers, backlighting LED modules and custom LED strips. In previous jobs Thomas was involved in lighting and large renewable energy projects. He was an SSL lighting technology teacher in vocational institutions in Italy with specific temporary assignments. Besides the lighting world, his passions include music, volleyball and cars.

Modern HCL Designs

Pages and pages have been written on the human body's adaptive response to its external environment. But we focus all our efforts primarily on one aspect: Light must be designed to support people in their daily activities and be beneficial to their health – visually, emotionally and biologically.

Sunlight synchronizes the day/night cycle, and thus also our internal clock that regulates our body in a 24-hour rhythm. By simulating the impact of natural daylight, biologically effective artificial light keeps us in sync with our outside world. While the color and intensity of the light are manually controlled in TW (Tunable White) applications, HCL (Human Centric Lighting) solutions autonomously adjust the brightness level and color temperature to the natural course of daylight – from activating cold white to relaxing warm white. In addition, parameters such as the level of daylight, the room structure and the user profile must be taken into consideration. Intelligent lighting control and sensor technology make it possible to align the light color and brightness level with the changes in daylight in order to stabilize our internal clock. The result: We feel more alert, can concentrate better and are more vital. Designing proper artificial light is more essential today than ever before because a growing number of people spend the vast majority of their time indoors where the lack of natural light must be compensated accordingly. Static artificial light can extend the day, but with HCL we make it more natural for us humans.

The market now offers excellent components, ranging from TW LED modules of high light quality, LED drivers that realize the mix of cool and warm white in high lighting quality, and lighting management systems that control the passage of time in quality and quantity as needed.

Diffusive lighting and spots can now be mixed to provide different spatial impressions. In addition, autonomous temporal sequences of light intensity must be defined in order to ensure that the right light is available at any time of day. When designing an HCL-ready luminaire, a spectral evaluation of the optical radiation in the visible range must be performed in order to enable the melanopic effects of light. This evaluation depends on various parameters:

- Brightness compared to glare
- Color temperature range and spectral deviations due to the application of reflector/optics material
- Filter effect of applied covers/diffusers, e.g. glass or stretched vinyl
- Transmission, reflection and absorption of walls
- Possible impact of daylight
- Different characteristics of the user (pupil diameter, age, etc.)

"The technical implementation of HCL solutions requires a qualified lighting design that is adapted to the spatial conditions."

THOMAS ZAMPIERI, OSRAM DIGITAL SYSTEMS

More detailed information is described in the standards DIN SPEC 5031-100 and DIN SPEC 67600.

Modern lighting systems open up great potential: DALI LED drivers wired or wireless with the latest Bluetooth Low Energy Mesh solutions are combined with various types of sensors and luminaires. All transitions, such as dimming or light color changes, occur smoothly and precisely – without stroboscopic effects, flashing, flickering or the like.

Today, the technical implementation of Human Centric Lighting solutions is easier than ever before, but requires a qualified lighting design that is adapted to the spatial conditions. ■

T.Z.

BUSINESS

Signify and Intelligent Waves Enter Into Strategic Collaboration To Deliver Mission-Critical LiFi Connectivity

Signify has entered into a strategic technology collaboration with Intelligent Waves, developer of the award-winning, cyber-defense solution, GRAYPATH. Together, Signify's game-changing LiFi solution, Trulifi, and the GRAYPATH software use invisible light waves to enable reliable, secure, two-way wireless data communication, providing defense personnel with mission-critical connectivity.

Signify's unique Trulifi solution offers physical security via dedicated USB access keys and a consistent, high-speed wireless connection through light, while GRAYPATH uses the cloud to randomize and distribute data across multiple paths and encrypted channels. The technology integration enables the secure transmission of data from high-risk operational locations without the danger of information being jammed, intercepted or disrupted.

"We are excited to offer our solution, in partnership with Intelligent Waves, to the defense industry," said Richard Honey, Head of Trulifi by Signify sales, US Defense sector. "Light-based communication, unlike conventional radio technologies such as Wi-Fi and 4G/5G, offers a critical, extra layer of security; it can be controlled within a restricted space and does not penetrate through walls. This benefit has already been recognized by defense customers, with the US Army, Navy and Marines adopting our game-changing LiFi technology."

John Hammes, Chief Strategy Officer of Intelligent Waves, said: "We are thrilled to partner with Signify, a pioneer in lighting and light-based communication. Together, we will be able to better serve the most demanding and secure special operators in austere environments, and we look forward to integrating Signify's innovation into the platform."

According to Joe Vano, Transmission Group Lead, Program Management Office – Tactical Network, Technical Management Division of the US Army, "LiFi can enhance the Low Probability of Intercept/Low Probability of Detection attribute on the battlefield. This secures the Tactical Operations Center (TOC) to a higher degree due to its insignificant and largely undetectable RF signature while maintaining high-speed connectivity within the TOC. Reducing our adversaries' ability to intercept and jam the battlefield Commander's network while still maintaining a network cable-free environment within the TOC is advantageous." ■

ams OSRAM Reaches an Agreement for Inventronics to Acquire the Digital Systems Business in Europe and Asia

ams OSRAM, a global leader in optical solutions, announced the agreement to sell the Digital Systems business in Europe and Asia to Inventronics, a global supplier of LED drivers. ams OSRAM will continue to focus on the high technology semiconductor business, as well as automotive, entertainment and industry lamps business. The transaction represents a further milestone in the implementation of ams OSRAM's strategy to focus on core technology areas in illumination, visualization and sensing, and to divest businesses that are not core to the company's strategy. The transaction is subject to customary closing conditions.

The ams OSRAM Europe and Asia Digital Systems business develops mainly power supplies with related light modules, software and connectable components for traditional and LED illumination. These are essential components for luminaires in professional lighting applications that enable smart lighting solutions and digitalization. With the acquisition of ams OSRAM's Europe and Asia Digital Systems business Inventronics will be able to expand its regional and portfolio scope.

"We are very excited about this transaction. We fully believe it will enable us to create even more value for our customers, employees and shareholders. The combined portfolio and capabilities, coupled with the fact that we will not be competing with our customers, should make us the first choice for LED drivers with a very large portion of the market," said Marshall Miles, CEO, Inventronics.

Dr. Wilhelm Nehring, EVP and GM Business Unit Digital at ams OSRAM: "Our goal was to select a buyer who offers a long-term perspective for our employees and our customers along with the ability to foster additional value creation for customers. Digital Systems and Inventronics share a passion for technology and this acquisition is based on a growth strategy, which provides an exciting future perspective for the business and employees."

"We look forward to joining the Inventronics family. Both companies have a deep market knowledge and customer understanding, and that, combined with our strong European and Asian presence, will enable us to continue to deliver excellent quality and leading-edge innovations to our customers," said Dr. Gernot Steinlesberger, Head of OSRAM Digital Systems Europe and Asia.

The Digital Systems business in Europe and Asia employs around 600 people. The business is headquartered in Garching near Munich, Germany, and operates in more than 35 countries worldwide.

Inventronics is a publicly traded company headquartered in Hangzhou, China. The company maintains global operations including manufacturing facilities in China, India and Mexico in addition to distribution centers in the US and the Netherlands. Sales offices are in major markets around the world servicing customers in more than 100 countries.

For more information on Inventronics, please visit `inventronics-co.com`. For more information about ams OSRAM please visit our website at ams-osram.com. ■

DOE Launches Prototype Phase of L-Prize Lighting Competition

The U.S. Department of Energy (DOE) launched the second, "Prototype" phase of its three-phase Lighting Prize (L-Prize®) competition, a DOE American-Made Challenge designed to spur groundbreaking innovation, stimulate American manufacturing, and give rise to the next generation of lighting in commercial buildings.

The Prototype Phase challenges entrants to pursue technological innovations that extend beyond the standard forms, materials, and price points of commercially available lighting products. Up to six competitors will share an award of $2 million.

"Investing in next-generation lighting solutions is key to tackling the climate crisis, boosting American supply chains and the manufacturing of these technologies, creating good-paying jobs, and Building Back Better," U.S. Secretary of Energy Jennifer M. Granholm said in January as she announced the winners of the L-Prize's Concept Phase at DOE's annual Solid-State Lighting Workshop. "We can't wait to see what innovations come out of the rest of the competition."

The L-Prize advances the state-of-the-art in LED lighting, encouraging innovators to develop advanced lighting systems that lead to transformative designs, products, and impacts. The challenging technical requirements are intended to stimulate innovation and raise the bar for efficacy, quality of light, connectivity, and long-term environmental impact. In addition to technical innovation, the L-Prize also prioritizes diversity,

Efficiency meets reliability for outdoor lighting

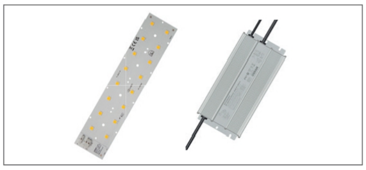
Long-lasting and energy-saving: the new LED systems from OSRAM DS ensure efficient lighting on streets, in parking lots and at sports facilities

In times of rising energy prices, efficient and sustainable lighting systems in public spaces are particularly in demand. The switch from conventional lighting to energy-saving LED concepts offers great potential for cost-optimized, high-performance lighting solutions – which also improve the carbon footprint.

OSRAM DS now extends its offer with new optimal solutions for this: the new PrevaLED Brick HP HE LED module focuses on high lumen output and very high efficiency.

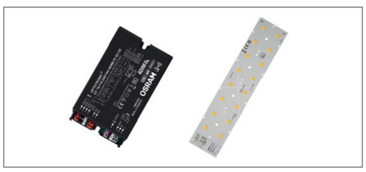
It complies with the Zhaga standard and can also be easily integrated into existing designs. This new LED module develops its optimum performance in combination with all our Outdoor LED driver families. They offer robustness, perfect lighting control and efficiency for several lighting systems: from streetlights to lighting solutions for areas and large-scale sports facilities. Besides the different product features and interfaces – from standard stand-alone dimming to the DALI interface, including DiiA parts 251/252/253 for luminaire data, energy reporting, diagnostics and maintenance, which enable future-proof IoT solutions – all OSRAM DS Outdoor LED drivers have one common denominator: no compromise on quality and reliability!

High performance for sports facility lighting
Robust and efficient lighting solutions are required for bright and low-glare illumination of outdoor sports facilities and plazas. PrevaLED Brick HP HE offers optimal performance with the LED drivers OT 2DIM P7 AUX12 High Power



Durable and long-lasting
The PrevaLED Brick HP HE LED module is ideally suited to outdoor requirements thanks to high ESD protection, long service life, high efficiency and lumen output and represents a sustainable solution, enabling new and material-saving design possibilities.

High performance and reliability for street lighting
In outdoor lighting, product failures can lead to very high secondary costs due to the complexity of the installations. Our focus remains on high performance and quality, and we do not make any compromises on the selection of components.



Customized and sustainable
OSRAM DS LED modules and LED drivers offer maximum flexibility in outdoor lighting. Efficiency and sustainability are always in focus. With our individual service, we always develop the right solution for our customers – including luminaire validation.

Customization is King: We offer individual service for our customers, and as a result develop the optimal lighting project. For more information visit **www.osram.com/outdoor** or contact our sales department directly: **expert-contact@osram.com**

Light is OSRAM

Matteo Toscan

Matteo Toscan is an expert in outdoor lighting systems and has been working in the lighting industry for many years. When developing efficient and sustainable solutions, he always keeps the favorable carbon footprint of our products in mind.

Rauno Pokall

Rauno Pokall is Senior Product Manager at OSRAM and an expert in customer solutions for LED modules in high-durability and outdoor applications. He also finds customized solutions for our customers in the growing horticulture market.

High performance for outdoor lighting

With LED modules and LED drivers from OSRAM DS you are ready for future-proof, robust and efficient outdoor lighting.

- The **PrevaLED Brick HP HE LED module** offers high lumen output and efficiency for compact construction and cost-efficient luminaire designs
- **OT 2DIM P7 AUX12 LED drivers** with 400 or 600 watts are suitable for large-scale outdoor lighting systems especially for parking areas and sports facilities
- **Outdoor LED drivers** together with the **PrevaLED Brick HP HE** LED module enable compact and efficient lighting solutions. Different product features and interfaces are available to meet the different connectivity needs, from stand-alone dimming to IoT-connected solutions. The common denominator: no compromises in quality and reliability

OSRAM. The light you need.

OSRAM Digital Systems delivers technology for successful LED projects. From components to complete systems, from individual solutions to large-scale installations. Whether in industry, at trade fairs, in parking garages or in retail stores – you can always rely on OSRAM quality components.

OSRAM

equity, and inclusion in how competitors develop and deploy lighting systems.

"The L-Prize is primed to unlock the full potential of LED technology–to combine high efficiency with exceptional lighting quality, data-driven control, and sustainable design and construction in a winning product that will redefine the future of lighting," said Dr. Carolyn Snyder, Deputy Assistant Secretary for Energy Efficiency.

The L-Prize's current Prototype Phase is divided into two separate tracks: a luminaire track and a connected systems track. Participants may develop prototypes in one or both tracks. The L-Prize expects to launch its third and final phase, "Manufacturing and Installation," next year. This phase will reward production and installation of products that meet the L-Prize's technical requirements. Up to four competitors will share an award of $10 million. ■

New Standards from IES

The Illuminating Engineering Society (IES) recently introduced four new standards documents addressing current challenges that face the lighting industry – navigating near-field photometry, standardizing iterations of lighting controls intent, the importance of UV lighting, and promoting a balanced outdoor environment. The four new standards are available in the IES webstore, and include:

Recommended Practice: Lighting Exterior Applications (ANSI/IES RP-43-22)
This document provides pedestrian-oriented illumination recommendations for the reassurance, safety, comfort, amenity, and enjoyment of people in outdoor environments. This RP takes a comprehensive approach and makes recommendations based on lighting zone, glare avoidance, spectrum, and other visually influential conditions. Application of these recommendations will ultimately enhance the visual experience for people, while also respecting the environment.

Lighting Practice: Documenting Control Intent Narratives and Sequences of Operation (ANSI/IES LP-16-22)
Intended for a variety of users in the lighting community, this document provides guidance on the documentation of Control Intent Narratives and Sequences of Operation. It is not intended to be a design guide, but rather a reference manual of best practices on how the design, once formulated, is included in the project documentation and communicated to the construction and commissioning teams.

Approved Method: Application Distance Radiometry (ANSI/IES LM-91-22)
In near-field conditions, the use of far-field IES-format photometric files results in substantially incorrect irradiance, illuminance, or photon-flux density values being predicted by lighting layout models constructed for near-field conditions. This problem can be overcome by using distance-specific IES file(s), generated by first collecting data at the working distance(s) of interest obtained from a single luminaire and then converting them to distance-specific IES file(s), following the protocol described in this document.

Approved Method: Optical and Electrical Measurement of Ultraviolet LEDs (ANSI/IES/IUVA LM-92-22)
This document is a guide developed for the measurement of ultraviolet (UV) light emitting diodes (LEDs) and describes the procedures to be followed and precautions to be observed in performing measurements of total radiant flux (total radiant power), electrical power, and wavelength characteristics of ultraviolet (UV) light emitting diodes (LEDs).

"The IES is committed to developing standards that address important and timely factors that influence the practice of quality lighting," says Brienne Musselman, IES director of education and standards. "As always, we are grateful to the contributors who helped develop these documents. Professional rigor remains a priority for us, and these standards represent an important step to solve the issues facing our community." ■

2022 Lightfair Innovation Awards Celebrate 18 Winners

LightFair has announced the winners of its 2022 LightFair Innovation Awards (LIAs) in 14 categories, along with four overall excellence distinctions: Most Innovative Product of the Year (MIFOR 70 Lighting System by Klus), Technical Innovation (TruBlu™ Bluetooth Mesh Fixture Controller with Long Range Antenna by McWong International), Design Excellence (Easy-Link by Edison Price Lighting) and Judges' Citation (CombiCable by Gripple) awards. The LightFair Conference and Trade Show runs through Thursday, June 23, at the Las Vegas Convention Center's West Hall.

"Our 2022 LIA winners continue to pave the path for lighting innovation," said Dan Darby, show director. "This year's winners took innovation to the next level and created products that not only serve an important purpose in lighting but also demonstrate exceptional design capabilities and outside-of-the-box thinking."

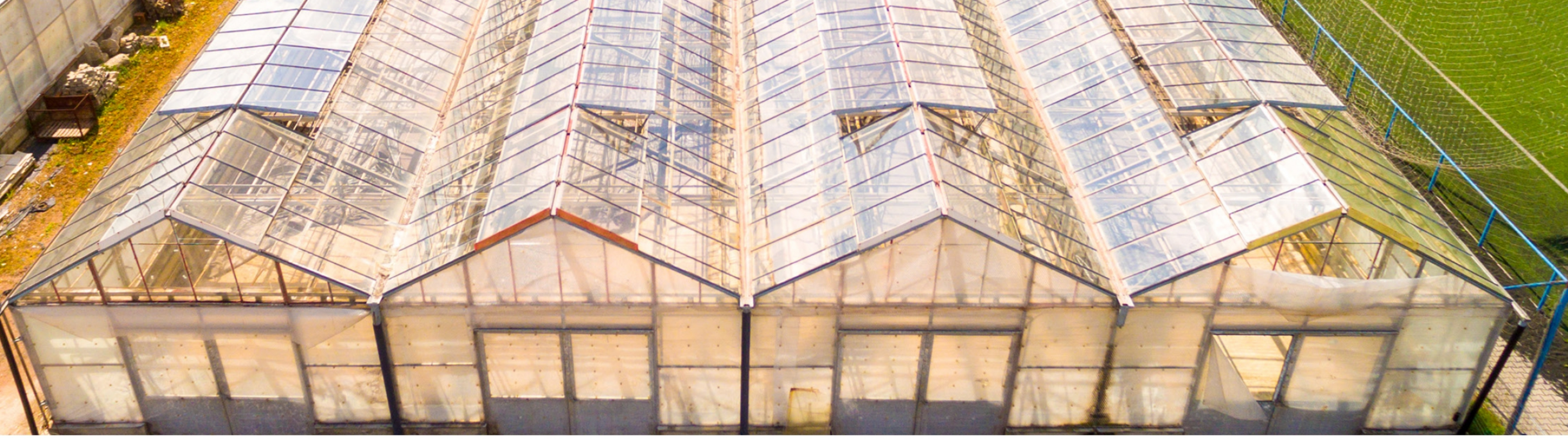
The 2022 LIAs recognize the most innovative products across 14 categories introduced since the October 2021 edition of LightFair. Category winners and special distinction honorees are:

- Most Innovative Product of the Year: MIFOR 70 Lighting System by Klus
- Technical Innovation: (TruBlu™ Bluetooth Mesh Fixture Controller with Long Range Antenna by McWong International
- Design Excellence: Easy-Link by Edison Price Lighting
- Judges' Citation: CombiCable by Gripple
- Indoor Decorative: MIFOR-70 Lighting System by Klus
- Control Components & Hardware: TruBlu™ Bluetooth Mesh Fixture Controller with Long Range Antenna by McWong International
- Commercial Indoor: Troffers, Suspended & Surface Mounted: Easy-Link by Edison Price Lighting
- Non-Luminous: Research, Publications, Lighting Software & Specialty Hardware: Labarazzi by Viso Systems Aps
- Lamps – Conventional, Retrofit & Replacement: LED PAR56 High Intensity Ultra Narrow Beam by LED Smart
- LED/OLED – Chips & Modules: OSLON Square Batwing by Ams OSRAM
- Ballasts, Transformers, Drivers, Systems & Kits: SmartSafe Emergency Backup for Low Temps by Keystone Technologies
- Dynamic Color, Theatrical, Cove, Strips & Tape: TruCirque by Pureedge Lighting
- Recessed Downlights, Wall Washers & Multiples: The LittleOnes™ by Usai Lighting
- Parking, Roadway & Area Luminaries: SiteLine by Anp Lighting
- Sports, Step, Landscape, Pool & Fountain Luminaries: Cuff Post Sconce by Wagner Architectural Systems
- Industrial, Germicidal, Vandal, Emergency & Exit: Hybrid Architectural Cylindrical Downlight with Upper Air UVC by Pure Lighting
- Track, Display, Undercabinet & Shelf: Aileron Track by Hevi Lite
- Control-Enabling Technology, Connectivity & Software: SmartLoop Screw-In Controller with SmartPort Technology by Keystone Technologies

Judges for this year's awards were an independent panel of lighting professionals: Lane Swainston and Javid Butler of Illuminating Engineering Society (IES) and Ellen Kuklinski and George Huang of International Association of Lighting Designers (IES). The judges were moderated by Mark Roush of IES. Judging criteria included the product's clarity of purpose, versatility, adaptability, sustainability, ease of use, design efficiency and aspects that enhanced human wellbeing, among others. ■

Gabriel Byrne, Lighting Association Ireland, elected to the LightingEurope Executive Board

The General Assembly has elected Gabriel Byrne, representing the Lighting Association of Ireland, to the Lighting Europe Executive Board.



"Gabriel's long experience in lighting, both as a company owner and as a leader of industry associations, will be of great value to the LightingEurope Executive Board," states Ourania Georgoutsakou, LightingEurope Secretary General. Gabriel is a long-standing member of the lighting business community in Ireland and was a founding member and the first Chairman of the Lighting Association Ireland (LAI). He is currently Chairman of Fantasy Lights Group, the company he founded more than 30 years ago, he remains a guiding member of the LAI, and is also President of the Electrical Industries Federation of Ireland (EIFI).

"I'm delighted to be appointed to the LightingEurope Executive Board and look forward to making a meaningful contribution to the work of the organization," says Gabriel Byrne.

"The Lighting Association of Ireland benefits greatly from the activities and expertise of LightingEurope and I am excited to join the body that guides the association," he adds.

"The work in LightingEurope today will shape the future of Europe's lighting industry for the next 5–10 years. Our members are collaborating to define sustainability for lighting across all applications and products and our team is working with regulators to draft rules that are easily understood and enforced and that accelerate the uptake of quality lighting. The LightingEurope Executive Board is regularly called upon to provide strategic direction to the association, and we very much welcome Gabriel's hands-on experience of the lighting industry and of consensus-building," Ourania adds. ■

LightingEurope Announces Winners of 2021 & 2022 President's Awards

LightingEurope president Lionel Brunet revealed how each of the recipients has impacted the organization's work and helped Europe's lighting industry move forward.

LightingEurope were excited to host their members in Paris on 31st May and 1st June for a General Assembly dinner and conference. On this occasion they also organized the LightingEurope 2021 and 2022 President's Awards ceremonies to celebrate individuals' outstanding contribution to the work of the lighting industry.

In a spirit of friendship among peers and on what was the first in-person meeting for over 2 years, Lionel Brunet, President of LightingEurope, revealed his choices, highlighting how each of the recipients has impacted the work of LightingEurope and helped Europe's lighting industry move forward. LightingEurope congratulates the winners of the President's Awards (in alphabetical order of family name):

2021: Nathalie Coursière from IGNES & Peter Hunt from The LIAbegingroup
2022: Otmar Franz from ams OSRAM & Fabio Pagano from ASSIL

Over the past two years LightingEurope members have continued to collaborate and exchange to help shape the future of Europe's lighting industry, addressing such topics as how to apply the new ecodesign, energy labelling and EPREL obligations to lighting products, how to accelerate the uptake of LED-based lighting systems with sensors and controls, how lighting contributes to sustainability, or how to prevent and quickly address online freeriding. ■

Neozoon Powered by Optisolis Wins Design Plus Award 2022

This year, Neozoon powered by Optisolis wins the Light + Building Design Plus Award in the "Exhibitors" category. Neozoon designed the mobile light according to the cradle-to-cradle principle and integrated NICHIA's Optisolis full-spectrum LEDs as the light source. The combination of design, technical excellence and sustainability convinced the jury of the Design Plus Awards, which will be presented at this year's Light + Building.

Sustainable design meets LED with natural light

Neozoon is both the name of Lukas Heintschel, Tim Pfeilschifter and Kilian Klepper's company and their portable LED lights, the start-up's first product. It can be attached to smooth surfaces like a suction cup and invites you to playfully interact with light and your own environment. "Our goal was to design a truly mobile lamp that can be produced sustainably, offers high quality of light and brings more play and interactivity into our living spaces," says Neozoon founder Lukas Heintschel, summarizing his team's vision.

By using NICHIA's Optisolis as the light source, the Neozoon team has managed to meet these requirements. Thanks to the integration of Optisolis LEDs, the battery-operated lamp provides pleasant light in daylight quality and with a color temperature of 3,000 Kelvin. Industry-wide, the spectrum of Optisolis comes closer to natural sunlight than any other LED.

With Optisolis color rendering index of over 97, Neozoon makes the variety of colors and textures around you appear more vivid, precise, and brilliant than any other LED product. In addition, it reduces unwanted lighting effects such as diffuse reflection and glare.

Optisolis solves the challenges of luminaire manufacturers

The Neozoon design allows the lamp to be used flexibly as a design highlight in the home or as a practical light source in the camper. Its natural light improves visual comfort and well-being and reduces eye fatigue. A study by the Fraunhofer IBP also confirmed this positive effect of full-spectrum LEDs. The portable Neozoon luminaire equipped with Optisolis shows that manufacturers from the furnishing sector have a flexible option with Optisolis to realize sustainable, creative and innovative lighting ideas. "The synergy between Neozoon and Optisolis is evident," says Anna Liza Müller, Business Development Manager at NICHIA: "The design of Neozoon mimics the shape of the sun and Optisolis imitates the sunlight almost to perfection."

Neozoon powered by Optisolis at the Design Plus Award

73 companies submitted 113 products for the Design Plus Award, which Messe Frankfurt presents every two years together with the German Design Council. A renowned expert jury honored the products that combine high design quality with innovative technology and sustainability in the fields of lighting, electrical engineering and building and home automation. The winning products can be seen at a special show in the Design Plaza (Hall 3.1, B 60) during the Light + Building Autumn Edition from 2 to 6 October 2022 in Frankfurt. At the NICHIA stand (Hall 8.0, D 60), visitors can also find out about the areas of application and possibilities of Optisolis. ■

TECHNOLOGIES

UV micro-LEDs for Sensing, Production and Communication

Researchers at the Ferdinand-Braun-Institut (FBH) in Berlin have successfully produced the first prototypes of micro-LEDs that emit in the ultraviolet spectral range (UVB). The micro-LEDs with 310 nanometers (nm) emission wavelength feature a small size of the emitting area with diameters down to 1.5 micrometers (µm). This is hundreds to thousands of times smaller than conventional UV LEDs. The micro-LEDs can be closely packed with pitches down to 2 µm to form a two-dimensional array on a chip, resulting in high-resolution UVB emitting areas.

Used either as single emitter or arranged as a high-density array, UV micro-LEDs can be used in a wide range of applications. This includes sensing technology, curing of polymers and resins, production of semiconductor chips, and optical communication. On FBH's current chips, all UV micro-LEDs of an array are operated simultaneously. In the next step, the LED pixels are to be individually addressed via a control chip. This will allow to generate and quickly modulate individual illumination patterns, enabling mask-free photolithography, for example. Individual structures can thus be created on semiconductor wafers easily, quickly, and cost-effectively. The capability of high-resolution UV irradiation patterns also opens up new applications in the field of rapid prototyping and fluorescence analysis. In parallel, FBH scientists are already transferring this technology to UVC LEDs, including far-UVC LEDs with extremely short emission wavelengths around 230 nm. Now, the FBH is looking for partners who intend to use UV micro-LEDs in their applications, aiming to jointly advance the technology and fully exploit the potential of the devices.

Highest demands on chip processing technology

Semiconductor layer structures emitting in the ultraviolet spectral range were deposited by means of metal organic vapor phase epitaxy and then patterned using lithographic processes, plasma etching, and deposition methods. Fabricating UV micro-LEDs with small diameters in the range between 1.5 and 50 µm and with a pitch between 2 and 60 µm required a high alignment accuracy, manufacturing precision, and material perfection. This could only be met by using state-of-the-art lithographic processes that were specially designed for this application. Precise alignment of the different process layers to each other (overlay control) with an accuracy of better than 20 nm over the 2" LED wafer was needed. Due to the small dimensions of the fabricated UV micro-LEDs – such as diameter, shape, and slope angle of the etched structures – their properties were controlled by means of electron microscopy. ■

Nichia Expands the LED Portfolio with 1800 K Emission Color, a True LED Alternative to HPS

Nichia announces the addition of the Direct Mountable Chip Series (Part Number: NVSWE21A-V1) to the portfolio of HPS color LED developed as a true LED alternative to High Pressure Sodium lamps ("HPS").

In July 2021, Nichia introduced the first HPS color LED, NVSW219F/1800K/Ra70. This has been highly acclaimed as an innovative and a unique product. HPS color LEDs maintain the nostalgic atmosphere of the landscape with the same emission color as HPS while enjoying the many advantages of LEDs, including greatly improved color rendering index, mercury-free, long lifetime, and instantaneous on/off. By adding the Direct Mountable Chip Series of LEDs to the HPS color LEDs' portfolio, customer options can be expanded and thus accelerate the transition from HPS to a mercury-free LED society. ■

Tiny Source Ensures Precise Beam Control and Color Quality

Lumileds newest high-power CSP LED is LUXEON HL1Z, an un-domed, single-sided, emitter that delivers high efficacy – 137 lm/W or more – from a very small package just 1.4 mm square.

The top emission prevents "cross-talk" and contributes to the superior color over angle performance and color consistency. Compactness and directional emission allow engineers to create tight arrays and precisely control the beam which enables smaller optical solutions and a path for system cost reduction. LUXEON HL1Z is particularly ideal for high center beam candle power applications such as high-end retail spots, tunable white solutions, aftermarket automotive, and other high density array lighting.

"Demand for the next generation of high power LEDs is increasing as the need for higher intensity, beam steering, compact arrays, color tuning, and high center beam candle power solutions become the drivers of new applications," said Alvin Yeoh, Product Manager.

Lumileds pioneered the high power LED space more than twenty years ago with LUXEON and the company continues to develop new and differentiated solutions like LUXEON HL1Z for lighting solution manufacturers.

"Lighting engineers are taking full advantage of the light output to size ratio that's unique to LEDs," said Yeoh. "Emitters like HL1Z provide new design freedom without sacrificing quality or efficacy."

LUXEON HL1Z is immediately available through Lumileds distribution network in CCTs from 3000 K to 6500 K and CRIs of 80 and 90. Additional CCT/CRI combinations will follow over the coming months and are available for pre-order. ■

XLamp® Element G LEDs for Color Mixing

Cree LED XLamp® Element G (XE-G) LEDs are for color-mixing lighting applications that require high levels of light output. The LEDs have full control over spectral content and are available in 17 different colors. There is also a complete portfolio of white options, for unprecedented flexibility to change and optimize product light output properties. ■

Luminus Gen 4 High Density COBs Leverage Robusto™ Technology

Luminus Devices introduces the next generation for high lumen density, white COB arrays featuring the latest enhancement to improve maximum operating temperature, Robusto technology. High lumen density parts are used in narrow beam applications where Center Beam Candle Power (CBCP) is the key metric.

While this depends on the specific beam angle and power level, the high lumen density parts typically deliver two times or greater lumen density than standard parts. Higher temperature operation means more luminaire design flexibility and lower potential cost with, for example, smaller, lighter heat sinks. These Generation 4 high lumen density parts provide stable lumen output and color points with temperatures as high as Tc = 120 °C. Robusto technology has the ability to enable higher drive currents while still delivering exceptional lumen maintenance (L90 > 55k hrs.) and remarkably stable color points.

This line of COBs has outstanding color quality, high lumen intensity, and the industry's best flux and color stability over their operating life, all of which make them the preferred solution for narrow beam, high CBCP applications in retail and shop lighting, hospitality lighting, architectural and specialty lighting.

David Davito, COB Product Line Director, Illumination at Luminus, shares why this new product line has so much to offer. "The new Generation 4 high lumen density parts offer the ultimate in COB flux density. This is complemented by Robusto technology which enables higher operating conditions while maintaining steady lumen maintenance and color stability. With Robusto technology, Luminus' high-density COBs are able to provide customers with higher levels of CBCP, consistent color and flux over the life of the luminaire." ■

ioXt to Secure Network Lighting Controllers

The ioXt Alliance, the global standard for IoT security, announced that a new round of Network Lighting Controllers (NLCs) have been certified through the ioXt Certification Program under its NLC Profile. As part of their efforts to increase the level of security in their products, top NLC manufacturers including GE Current, Eiko Global and Digital Lumens, Inc., tested and earned their ioXt Certification after meeting the ioXt's rigorous standards, which fulfills the NLC5 technical requirements set forth by the DesignLights Consortium (DLC).

Buildings are becoming more connected and interoperable, and the smart commercial lighting industry is leading the way in this evolution. While this allows for more innovation across the commercial building industry, vulnerabilities in 'smart' products and systems like light bulbs and NLCs, in particular, have remained in the spotlight in recent years as a proven point of entry for cyber criminals in gaining access to large-scale networked systems.

"With the increase of threats and vulnerabilities across the IoT ecosystem, the lighting industry has become a target, making a critical need for strong security measures and industry-led standards that help put secure and safe products on the market," said Jan Bondoc, VP of Information Technology at the ioXt Alliance. "GE Current, Eiko Global and Digital Lumens proactive step in certifying their NLCs through ioXt, represents their commitment to security and safety. Together, with the DLC and our partners, we continue to push the envelope for the IoT community."

To meet the increased demands for safer connected devices across the IoT ecosystem, the ioXt Alliance recently expanded its certification program to include NLCs, advancing the industry's efforts to improve the security and transparency of wireless commercial lighting systems. Through this profile, NLCs are tested and evaluated against eight ioXt pledge principles for quantifying the optimal level of security. These guidelines are centered around security, upgradability, transparency, and compliance

"Many of our NLC customers have concerns with cybersecurity and privacy. ioXt certification gives our customers added confidence that we meet and adhere to a strong set of industry standards," said Jason Sherrill, VP of Controls and Software at GE Current. "ioXt has raised the bar in customer awareness for privacy and security with end customers. GE Current is proud to have NX Lighting Controls and Daintree Wireless Controls certified with ioXt and adhering to stringent cybersecurity and privacy protocols."

"As an early innovator in the networked lighting controls space, Digital Lumens, Inc. has always viewed the security of our product design as fundamental to our mission to build secure and reliable systems," said Jeff Campbell, LC, Sr. Director of Product at Digital Lumens, Inc. "We welcome the opportunity to partner with the ioXt Alliance and certify the capability of our Digital Lumens SiteWorx® and Encelium® X solutions."

All ioXt certified NLCs meet the DLC's cybersecurity requirements and the product is eligible for qualification, which is required for many rebates offered by efficiency programs throughout North America. The most recent deadline to submit a new system was on April 15. The current submission period began on April 16, with July 31 as the last day of this period.

To learn more about the ioXt Alliance, visit ioxtalliance.org and for more information about the NLC profile, visit ioxtalliance.org/nlc. For more information on the DLC's cybersecurity requirements, visit designlights.org. ■

Magna Illuminates the Future of Styling With Breakthrough Lighting

Exterior lighting is increasingly becoming a central styling differentiator while helping to improve safety through greater visibility. Magna's Breakthrough Lighting solution featured on the thermoplastic liftgate known as Litgate, combines the company's expertise in exteriors and lighting and offers new ways to personalize and allow consumers to interact with their vehicles. Magna plans to have the technology ready for production in 2023.

"Magna's Breakthrough Lighting enables increased design freedom and features more options for brand differentiation that can elevate our customers' experiences," said Grahame Burrow, Global President of Magna Exteriors. "As the industry builds significant momentum around electrified and autonomous vehicles, we expect more desire for developments like this that are seamlessly integrated into exterior surfaces."

Magna's competitive advantage is its ability to create solutions leveraging a full-systems approach. Uniting Magna's in-house capabilities in exteriors and lighting early in the vehicle development and design process creates synergies that allow for more holistic product development.

Breakthrough Lighting enhances the overall appearance as well as function of lighting by refining communication between the user, the vehicle and its surroundings including key differentiators such as:

- Breakthrough hidden-until-lit light effects
- Communicative, functional and decorative lighting
- Molded-in styling features and intricate textured surfaces
- Extensive color palette available, programmable to customer spec

Breakthrough Lighting technology is applicable on thermoplastic material surfaces including polycarbonate and thermoplastic polyolefins. Through materials, coatings and processing advancement, the desired lighting effects are achievable on various exterior panels. Magna offers its customers a wide choice of lighting solutions, each with specific characteristics that are designed to help achieve striking and captivating brand identities. ■

PLEXIGLAS® for Zumtobel's Moisture-proof AMPHIBIA PM Luminaire

Dust swirls through the air, water splashes, cleaning agents are sprayed – luminaires in industrial buildings have to cope with a lot of adverse conditions. They are often exposed to dirt, humidity, extreme temperatures or even chemicals.

The materials have to withstand all these impacts, as well as being break and shock-proof. Workplaces are also subject to complex requirements for light quality and illumination.

Zumtobel, a leading international provider of lighting solutions for commercial properties, developed its robust AMPHIBIA moisture-proof luminaire for an extremely wide range of industrial applications. The long LED diffuser luminaire lights up factories, logistics centers, agricultural buildings, parking garages and much more. It is available in three versions, adapted to different areas of use. Zumtobel produces one of these, the AMPHIBIA PM, from PLEXIGLAS® molding compounds, the brand polymethyl methacrylate (PMMA) from Röhm. "Our material meets the high standards needed for industrial lighting and also offers outstanding lighting properties," says Andrea Fruth, Senior Product Manager Lighting, Extrusion, Optics in the Molding Compounds business unit of Röhm GmbH.

The same material for diffuser and housing

Both the housing and the diffuser of the AMPHIBIA PM are made from the PLEXIGLAS® Resist zk5BR special molding compound. It is where the versatility of the highly transparent, impact-resistant material, which can also be equipped with diffuser particles for an opalescent look, really comes into its own. "Our one-material concept for the housing and diffuser was unique when AMPHIBIA was launched. It ensures optimum resistance throughout the luminaire's entire lifespan," explains Thibaut Escourrou, Global Product Manager at Zumtobel. The advantage of using the same material for the entire product is that everything has the same thermal expansion properties. This ensures that the luminaire remains watertight, even when exposed to significant fluctuations in temperature.

But its versatility is just one of the reasons why Zumtobel chose PLEXIGLAS®. "We value PLEXIGLAS® Resist zk5BR for its very high transparency," says Escourrou. "PMMA's high UV resistance is also an advantage for luminaires used outdoors and in covered outdoor areas, such as in agricultural settings." This is because the material's integral UV protection allows PLEXIGLAS® to retain its optical properties permanently, without weather conditions causing it to become yellow or brittle.

Extraordinary transparency and high surface reproduction accuracy

Zumtobel's experts have developed a range of light scenarios for the AMPHIBIA series, tailored to various room dimensions and ceiling heights. For example, the luminaire can be equipped with very narrow beam angle optics for illuminating high-shelf logistics centers. PLEXIGLAS® Resist zk5BR is extraordinarily transparent and combined with its high surface reproduction accuracy in injection molding, the special molding compound is ideal for high-precision optical components like this. In the AMPHIBIA luminaires, linear microstructures at the bottom of the transparent cover guide the light to cover a deep or wide area, exactly as needed.

"PMMA is the only real choice of material when it comes to lighting technology. It allows us to achieve maximum light yield and efficiency," agrees Wolfgang Bechter, Global Project Manager at Zumtobel. "AMPHIBIA is designed for a lighting duration of 100,000 hours, so we place great importance on selecting the best material for a long lifespan. From this point of view, too, PLEXIGLAS® molding compounds from Röhm meet Zumtobel's quality standards."

Resistant to cleaning agents

The lifespan of industrial lighting depends not only on the material's resistance, but also on the product being able to withstand dirt and moisture and being easy to clean. Designer Stefan Ambrosius and his development team therefore designed AMPHIBIA's geometry in such a way that as little dirt as possible adheres to it while water simply runs off the smooth surfaces and rounded edges. With its extremely robust housing, which keeps out all dust and water, AMPHIBIA meets the requirements for the IP66 safety class and can withstand even the water jet from a pressure cleaner.

The fact that the entire luminaire is made from transparent components also has a very practical reason when it comes to cleaning: "You can see from below whether dirt has collected on the top of the light and needs to be cleaned. That was one of the customer's hygiene requirements," explains Escourrou. "The PMMA variant offers outstanding resistance against a large number of chemicals that are commonly used in food processing plants, including cleaning agents." ■

VCSEL Testing in Production Lines

Quality control of VCSELs and EELs in production lines requires the full optical characterization of a device-under-test (DUT) within milliseconds. For this, the combination of an integrating sphere (ISP series) and a high-resolution array spectroradiometer of our CAS series is the ideal system for fast and reliable tests of semiconductor laser diodes, determining key characteristics like the centroid wavelength and the radiant power.

The high measurement speed requires that such spectral measurements are usually carried out with only a single, millisecond long optical pulse in the integration time window of the spectroradiometer.

In such systems, the integrating sphere homogenizes the light field and the array spectroradiometer has to record the laser spectrum with the necessary accuracy and measurement speed. For light sources with a very narrow spectrum, the precision of the radiant power measurement can be further increased with an additional photodiode sensor attached to and calibrated with the ISP. This is recommended for high precision measurements to correct deviations due to the wavelength-dependent reflectivity of the DUT and its surroundings with the self-absorption correction method. For this, it is necessary to choose an appropriate auxiliary light source with a suitable spectral power density distribution. The narrow spectral bandwidth of VCSELs – typically in the range of a nanometer – requires spectroradiometers with sub-nanometer spectral resolution. Instrument Systems offers with the CAS 140CT-HR, the CAS 120-HR and the CAS 100-HR three high-resolution spectrometer platforms and additionally integrating spheres and suitable auxiliary light sources for semiconductor laser diode testing in production lines. A new fast InGaAs photodiode specially designed for nanosecond pulsed VCSEL measurements (as used in LiDAR or Time-of-Flight 3D sensing applications) completes the portfolio. ■

Newly Developed Technique to Improve Quantum Dots Color Conversion Performance

Quantum dots color conversion (QDCC) has become a foundational technology in the design of full-color light-emitting devices with dramatically improved color performance. However, conventional QDCC pixels fabricated by inkjet printing, that is commonly used, are still too thin to achieve efficient color conversion. A research team has developed perovskite quantum dots microarrays with strong potential for QDCC applications, including photonics integration, micro-LEDs, and near-field displays.

A research team has developed perovskite quantum dots microarrays with strong potential for QDCC applications, including photonics integration, micro-LEDs, and near-field displays. The team published their findings on May 31, 2022 in Nano Research. DOI 10.1007/s12274-022-4466-4.

In printing, QDCC is considered a versatile way to achieve full-color organic light-emitting diodes and micro-light-emitting diodes displays. QDCC provides a wide range of color performance and easy integration. However, the conventional combination of quantum dots and coffee-ring effects or puddle of particle-laden liquid that occur after evaporation, lowers the light conversion efficiency and emission uniformity in quantum dot microarrays. This also contributes to blue-light leakage or optical crosstalk, where unwanted coupling occurs between signal paths.

Perovskite quantum dots (PQDs) hold potential as an attractive material and can resolve some of the problems found in conventional QDCC. PQDs are made from the mineral perovskite. While perovskite quantum dots are relatively new, they have already been shown to have attractive properties that make them extremely suited for electronic and optoelectronic applications. By using patterned black photoresist molds to make the QDs pixels, researchers have been able to increase the pixel thickness and avoid the optical crosstalk, a common but significant issue which prevents better printing results. But the manufacturing costs increased substantially. The research team set out to resolve these challenges by developing a method that creates PQDs with a robust 3D structure.

"To solve these problems, we fabricated 3D perovskite quantum dots microarrays by combining the inkjet printing and in-situ fabrication of perovskite quantum dots during the photopolymerization of precursor ink," said Gaoling Yang, an assistant professor in the School of Optics and Photonics at Beijing Institute of Technology. Inkjet printing is a widely used deposition method for inorganic and organic optoelectronics. With its non-contact, material-efficient and reproducible processing, it has attracted attention in patterned microarrays. Photopolymerization is a technique that uses light to create a polymer structure. Using the photopolymerization technique, the researchers achieved a perovskite quantum dots color conversion microarray with a pixel size of 20 microns. Their technique provides a new technical route for light conversion applications, such as color conversion micro-LED.

The fabricated PQDs microarrays exhibit characteristics that are desirable for QDCC applications, including 3D morphology with hemisphere shape and strong photoluminescence. These microarrays achieved strong and uniform photoluminescence in large area because of the seamless integration with in situ-fabricated PQDs. The researchers' technique demonstrated the potential use of the in situ direct print photopolymerization method for fabricating patterned multicolor perovskite quantum dots microarrays with both wide color gamut and high resolution.

The researchers' results further confirm the realization of high-quality multicolor microarrays through the inject printing approach. Looking ahead, the team sees potential applications for their work. They are confident that this technique paves the way for the further fabrication of full-color QDCC micro-LED displays. "The in situ direct print photopolymerization technique allows for precise control of the pixel structure, removing the aggregation of QDs and coffee-ring effects in microarrays, which will aid in their expansion in photonics integration, full-color display, on-chip biomedical diagnostics, and next-generation augmented reality and virtual reality devices," said Yang.

The research team includes Xiu Liu, Jianjun Li, and Yuejin Zhao from the School of Optics and Photonics, Beijing Institute of Technology; and Pingping Zhang, Weitong Lu, and Haizheng Zhong from the MIIT Key Laboratory for Low Dimensional Quantum Structure and Devices, School of Materials Sciences & Engineering, Beijing Institute of Technology; and Gaoling Yang who works at both the Beijing Institute of Technology and the MIIT Key Laboratory.

This research was funded by the National Key Research and Development Program of China, the National Natural Science Foundation of China, the National Natural Science Foundation of China, and the Beijing Institute of Technology Fund Program for Young Scholars Research. ■

ZKW Equips New All-electric Volvo C40 with High-tech Lights

The new Volvo C40 relies on LED lighting technology from Wieselburg-based automotive specialist ZKW. The headlight of the all-electric electric crossover has a pixel module with 84 individually controllable LEDs.

The high-tech light illuminates the road particularly efficiently, adapts dynamically to traffic and avoids dazzling other road users. A front camera and radar permanently scan the road, allowing up to five vehicles to be blanked simultaneously. The design of the high-quality pixel LED light is unique: the hammer-shaped light arc sets visual accents that are distinctive for Volvo. "For Volvo, we develop distinctive headlight designs that impress with their innovative technology and memorable appearance and increase road safety," explains Dr. Wilhelm Steger, CEO of the ZKW Group.

Smart LED pixel light
The headlight in the new C40 combines daytime running light, position light and turn signal light in a particularly compact form. An adaptive lighting system with camera and radar sensor ensures a high level of road safety by optimally illuminating the road without dazzling oncoming traffic. This is achieved by individually controllable LEDs combined in the pixel module. A front camera and the radar eye detect oncoming vehicles or vehicles in front and activate or deactivate the LED light in the headlamp's pixel module via the control unit. Despite the compact dimensions of the front headlamp, the system achieves a high light output. The unique LED light was developed in Wieselburg, where the headlight is also manufactured. The pixel module electronics come from the ZKW electronics plant in Wiener Neustadt.

Super-flat projection modules
The powerful light output of the premium headlamp is achieved by the LED pixel module in combination with the innovative ForTIR elements. The so-called light finger ForTIR elements use the apron to project part of the low beam onto the road. These are particularly flat projection modules that are just 13 millimeters high and also serve as design elements in the main headlights. The front headlamp's light design, typical of Volvo, has the characteristic "Thor's Hammer" shape, in which special attention was paid to homogeneity. This design element is formed via the light guides and thick-wall optics in front of it, and unmistakably represents the C40 as a Volvo. "The combination of 84-LED pixel module, light finger ForTIR* elements and Thorhammer design is unique to Volvo," Steger explains. ■

How Scientist Tested the Effect of Multicolor Lighting on Improving People's Psychological State

As missions for deep space exploration and space habitats are put on the agenda, astronauts need to withstand being tested by multiple stressors in confined and isolated conditions during such long flights, especially because in deep space exploration, problems such as signal delays make astronauts feel the anxiety of being far away from Earth and the psychological fear of deep space.
According to a series of experiments conducted recently on Earth and during current space missions aboard the International Space Station (ISS), NASA believes that monotony of vision, in particular, aggravates the crew's anxiety, irritability, depression. Moreover, a large number of studies have also found that crew members on long-term missions on the Antarctic Space Simulation Station are extremely susceptible to psychological problems caused by visual monotony and monochromatic colors. In a research paper recently published in Space: Science & Technology, Ao Jiang from European Space Agency conducted a study to test whether multicolor lighting can improve people's psychological state in an isolated and confined environment over a period of seven days.

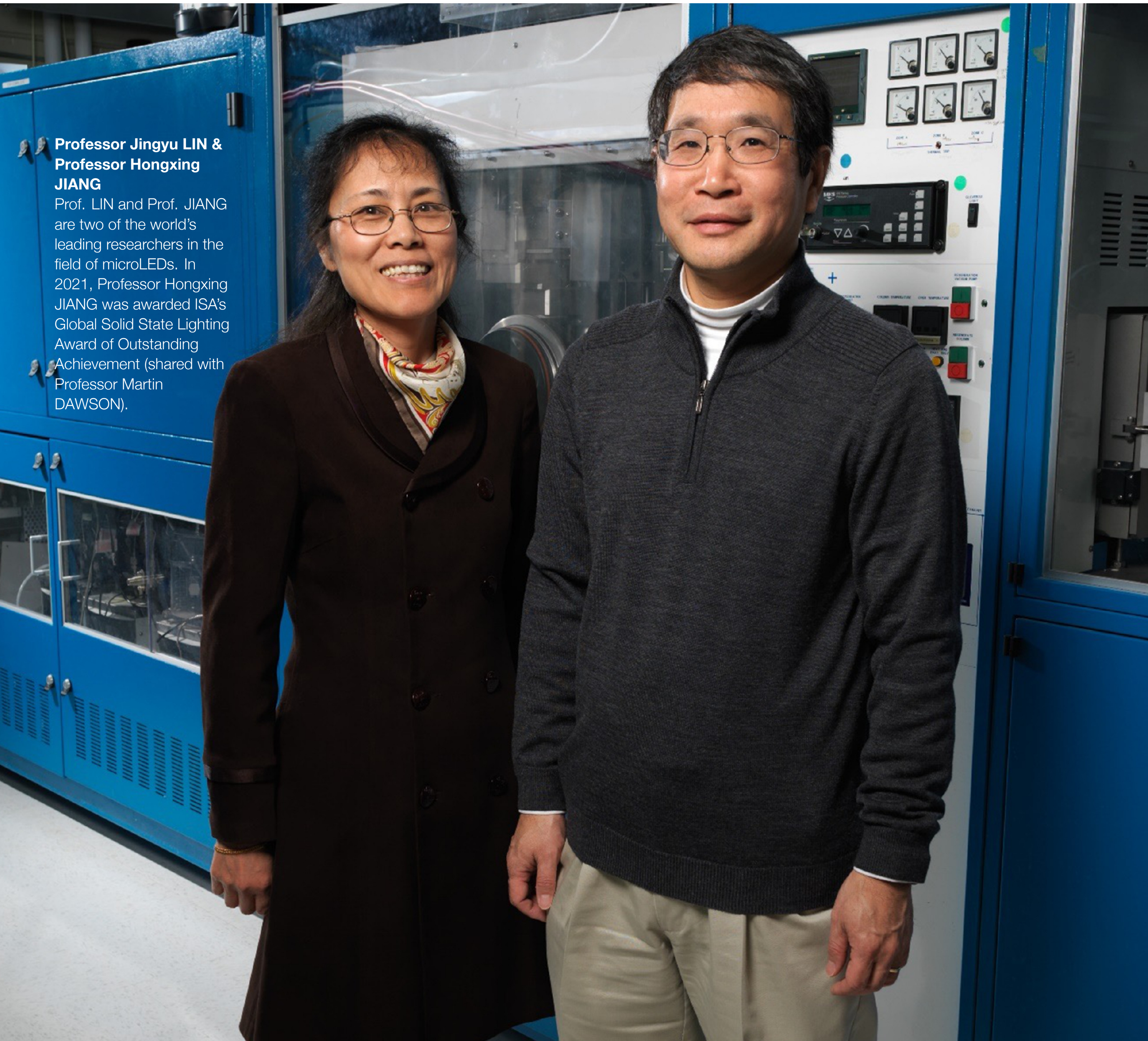
The author first prepared the necessary materials and methods. Twenty healthy participants (10 males and 10 females, all of Chinese nationality and mostly 21 to 27 years old) from Xiangtan University were selected. Twenty isolation wards of the Xiangtan Central Hospital were used, which were all 3.5 meters long, 3 meters wide, and 2.2 meters high. Each room was furnished with a chair and a table, a bed, and a bedside table. The walls and the ceiling were painted white and the floor dark grey These were the two main colors, apart from the door, chair, table, and dresser, which were a light wood color. Neutral colors were used to reduce any effects of the room on the colors to be used in the experiment. Moreover, Philips Hue Bluetooth wireless 16 million color dynamic light bulbs were chosen to project the colored light in the multicolor lighting rooms. The multicolor lamp was placed in the middle area between the desk and the bed in the isolated room to ensure that the participants were affected by the multicolor lighting in most daily activities. Besides, the PANAS questionnaire, a self-report measure, were used to assess the specific states that emerge from general dimensions of positive and negative emotional experiences, and the GAD-7 questionnaire, a one-dimensional scale, were designed to assess the presence of the symptoms of generalized anxiety disorder (GAD). As for statistical analysis, a chi-square general linear model repeated measures (GLM-RM) was used to measure the effect of isolation on emotion, anxiety, and self-rated health scores.

When the experiment got started, twenty participants were randomly divided into two groups: one group that was exposed to multicolor lighting and a control group, which was exposed to a static, monotonous white interior. In the multicolor lighting group, from 8 a.m. to 10 p.m. every day, the color of the multicolor light was randomly changed every three hours. Each participant entered a separate isolation room. During the isolation, the participants were not allowed to use any carriers such as mobile phones, computers, TVs, or iPads. But they could read paper books and do yoga and other activities. The participants' psychological state was recorded on the first day, the fourth day, and the seventh day. At 4:00–5:00 p.m. on the test day, the experimenters asked the participants to start filling out the paper questionnaire. After the questionnaires were completed, semi-structured interviews were conducted to record the participants' self-evaluation and subjective feelings. Each interview lasted about 5-10 minutes and was recorded for subsequent transcription and qualitative analysis.

The results of the control group showed that the participants' negative emotions and anxiety continued to increase over time, whereas the group randomly exposed to multicolor lighting that changed every three hours did not show any significant increase in negative emotions and anxiety. The most significant effect was observed on the fourth day, GLM-RM analysis indicated that the anxiety level on the fourth day was significantly higher than that on the first day in both groups. On the seventh day of the experiment, the anxiety level was also significantly higher than that on the first day, but there was no significant difference between the level of anxiety on the fourth day and on the seventh day. In conclusion, multicolor lighting was found to alleviate the increase in anxiety and negative emotions caused by isolation and confinement. Moreover, the random change of light color in the isolated environment appeared to help the participants get an increased sense of surprise to counteract the monotony of the isolation, with an effect similar to that of circadian lights. In future space exploration, colored lighting or other sensory adjustment interventions could be used in addition to teamwork and collective life to reduce negative emotions and anxiety feelings.

Reference:Author: Ao Jiang, Irene Lia Schlacht, Xiang Yao, Bernard Foing, Zhixiong Fang, Stephen Westland, Caroline Hemingray, and Wenhao Yao. Title of original paper: Space Habitat Astronautics: Multicolour Lighting Psychology in a 7-Day Simulated Habitat. Article link: https://doi.org/10.34133/2022/9782706. Journal Title: Space: Science & Technology. DOI: 10.34133/2022/9796015 ■

Bright Future for MicroLEDs, J.Y. LIN, H.X. JIANG, Texas Tech University, Lubbock, USA



Professor Jingyu LIN & Professor Hongxing JIANG
Prof. LIN and Prof. JIANG are two of the world's leading researchers in the field of microLEDs. In 2021, Professor Hongxing JIANG was awarded ISA's Global Solid State Lighting Award of Outstanding Achievement (shared with Professor Martin DAWSON).

Professor Hongxing JIANG and Professor Jingyu Lin work in the field of wide bandgap semiconductors and photonic devices and are the original inventors of nitride semiconductor microLED and microdisplay. In 2000, a research team, led by Hongxing JIANG and Professor Jingyu LIN realized the operation of the first microLED and passive driving microLED microdisplay. In 2009, their team, together with their colleagues, patented and realized the first active driving high-resolution and video-capable microLED microdisplay in VGA format (640 × 480 pixels) via heterogeneous integration of microLED array with a Si CMOS active-matrix driver, which has been adopted as a standard driving scheme for the development of microLED microdisplays today.

LED professional: If we may, we'd like to ask you about your personal and professional backgrounds first.

J.Y. LIN, H.X. JIANG: I, Hongxing Jiang, received my BS in Physics in 1981 from Fudan University, China. I came to the US through the CUSPEA program created by Nobel laureate, Prof. Tsung-Dao Lee. I obtained my PhD in Physics in 1986 from Syracuse University. I have been working on III-nitride wide bandgap semiconductors since 1995. Currently, I'm a Paul Whitfield Horn Distinguished Professor and Edward Whitacre endowed chair of Electrical & Computer Engineering within the Edward E. Whitacre Jr. College of Engineering at Texas Tech University (TTU). In 2008, together with my wife Prof. Jingyu Lin, we relocated our research group to TTU from Kansas State University where I was a University Distinguished Professor of Physics. I was elected to the Fellowships of the National Academy of Inventors (NAI) in 2018, the American Association for the Advancement of Science (AAAS) in 2016, the American Physical Society (APS) in 2010, the Optical Society of America (OSA) in 2014, and the International Society for Optics and Photonics (SPIE) in 2015. In 2021, I was honored by the International SSL Alliance (ISA) with its "Global SSL Award of Outstanding Achievements" for the invention of microLED in 2000.

I, Jingyu Lin, received my BS in Physics in 1983 from State University of New York at Oneonta. I obtained my PhD in Physics in 1989 from Syracuse University, where I met Hongxing and we

Figure 1: Professor Hongxing JIANG received the Global SSL Award of Outstanding Achievement for his research in the field of microLEDs, given by the International Solid-State Lighting Alliance.

Figure 2: Texas Tech University (TTU), 2500 Broadway, Lubbock, TX 79409, United States.

shared the same academic advisor. Currently, I'm a Paul Whitfield Horn Distinguished Professor and Linda F. Whitacre endowed chair of Electrical & Computer Engineering and co-director of the Center for Nanophotonics within the Edward E. Whitacre Jr. College of Engineering at Texas Tech University (TTU). I'm an elected fellow of the National Academy of Inventors (2019), the American Association for the Advancement of Science (2018), SPIE – the international society for optics and photonics (2017), the Optical Society of America (2016), and the American Physical Society (2012).

LED professional: Can you please explain how microLEDs are technologically constructed? Which structures are available and what types of microLEDs are currently available?

J.Y. LIN, H.X. JIANG: Originally, microLEDs were referred to micro-sized LEDs fabricated from InGaN/GaN quantum well structures. Today, the widely available microLEDs emit blue, green, and red colors. Large size microLED flat panel displays and TVs are now commercially available. Blue and green microdisplays fabricated from microLEDs have also become available.

LED professional: What are the benefits of reducing the size of LEDs to microLEDs for technologies and applications?

J.Y. LIN, H.X. JIANG: Back in the 1990s, III-nitride blue and green LEDs were already established to possess high efficiency and brightness, wide color gamut, and a long lifetime. One of the obvious benefits of reducing the LEDs' size to microLEDs is the ability to provide higher spatial resolution, which has been utilized today to manufacture large flat panel displays and TVs with exceptional high resolution. On the other hand, microLEDs are required for realizing microdisplays for wearable displays. Other unique features demonstrated for microLEDs by our group in the 2000s included increased turn on and off speed and enhanced light extraction efficiency over the conventional broad-area LEDs. Overall, in comparison with other technologies such as LCD and OLED displays, the exceptional features of microLEDs, including self-emissive, ultra-high resolution/brightness/contrast, ultra-low power consumption, wide color gamut, environmental stability, long lifetime, and fast on/off response time, are widely recognized today as important advantages for next generation displays.

LED professional: What are the main areas of applications you see to apply microLEDs? Do you also see general lighting, automotive lighting and communication as part of the microLED areas?

J.Y. LIN, H.X. JIANG: MicroLED and microdisplays are currently under intensive pursuits by almost all the big names in the tech industry for (a) large flat-panel displays/TVs, (b) smart watches, (c) smart phones, (d) i-glasses, (e) dashboard- and pico-projectors, (f) 3D/AR/VR displays. In particular, the sub-nanosecond response of microLED has a huge advantage over other display technologies for 3D/AR/VR displays since these devices need more images, more pixels per image, more frames per second and fast response. Another area in which microLEDs can make a large impact is in the medical applications for neutron stimulation and neural probe. The most important advantages of microLED for applications of neural stimulation/optogenetics are its array formation ability, comparable size with neurons, as well as high spatial resolution and high speed in comparison with a conventional LED; and it has a lower light intensity in comparison with a micro-laser that may

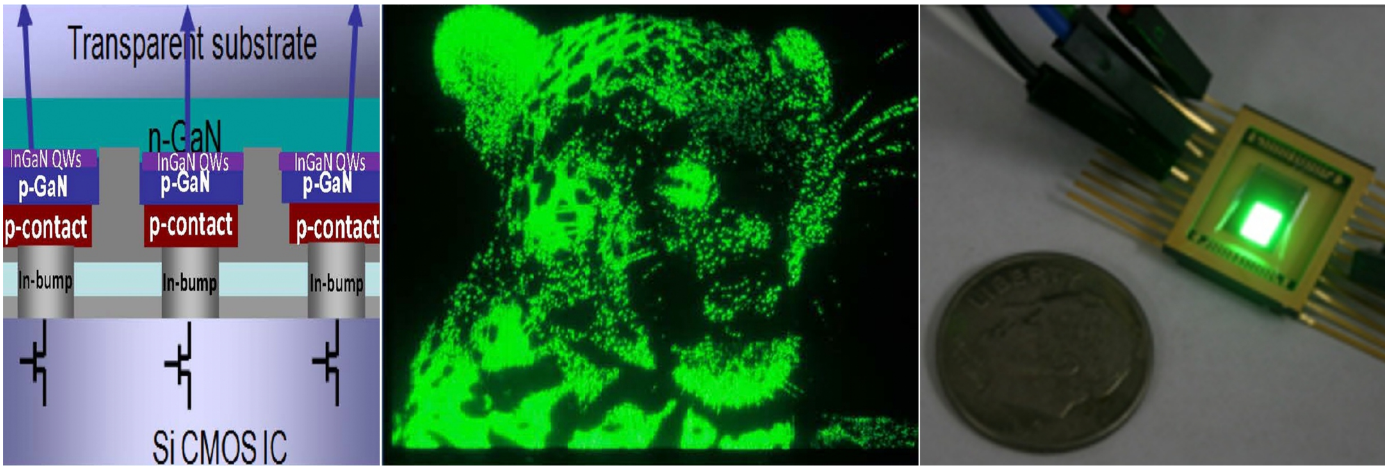


Figure 3: **The first monochromatic (blue or green) full-scale III-nitride microLED microdisplay in VGA format (640 × 480 pixels, 12 µm pixel size and 15 µm pitch distance) capable of playing video graphics images realized by Jiang, Lin and colleagues:** (**left**) Illustration of flip-chip bonding between microLED matrix array and Si CMOS driver IC via indium bumps to form a highly integrated active driving microdisplay in one package. (**middle**) A grayscale projected image (7.2 mm height × 9.6 mm width) of a leopard from a green VGA InGaN microdisplay (having 640 × 480 pixel with a pixel size of 12 µm and a pitch distance of 15 µm) operating at a driving current of 1 µA per pixel. (**right**) Photo of a laboratory prototype VGA microdisplay (having 640 × 480 pixel with a pixel size of 12 µm and a pitch distance of 15 µm) in action (Curtsey of III-N Technology, Inc.). Reproduced from US patent 9047818, J. Day, J. Li, D.Y. C. Lie, C. Bradford, J. Y. Lin, and H. X. Jiang, "III-Nitride full-scale high-resolution microdisplays," Appl. Phys. Lett.99, 031116 (2011). doi:10.1063/1.3615679 and SPIE Newsroom, Dec. issue (2011) doi: 10.1117/2.1201112.004001.

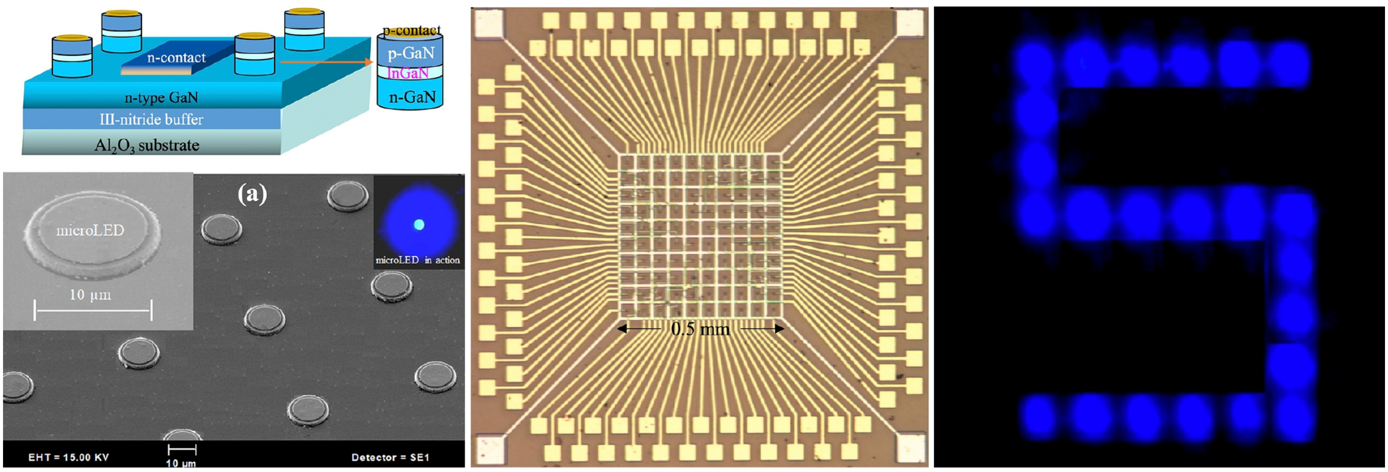


Figure 4: (**left/top**) Schematic layer structure diagram of an InGaN/GaN QW microLED (microLED) array; (**left/bottom**) SEM image of an InGaN/GaN QW microLED array with a microLED pixel diameter of 12 µm, pitch 15 µm and *p*-type Ni/Au contact diameter of 10 µm; (**middle**) Optical image of the first microdisplay (10 × 10 pixels) fabricated from the microLED array in (left/bottom) via a passive driving scheme); (**right**) Optical image of a blue microdisplay (10 × 10 pixels) in action. Reproduced from S. X. Jin, J. Li, J.Z. Li, J.Y. Lin and H. X. Jiang, "GaN Microdisk Light Emitting Diodes," Appl. Phys. Lett. 76, 631 (2000) doi: 10.1063/1.125841 and H. X. Jiang, S. X. Jin, J. Li, J. Shakya, and J. Y. Lin, "III-Nitride Blue Microdisplays," Appl. Phys. Lett. 78, 1303 (2001). doi: 10.1063/1.1351521.

Technology	LCD	OLED	III-nitride μLED	DLP	LBS
Mechanism	Backlighting/LED	Self-emissive	Self-emissive	Backlighting/LED	Backlighting/LD
Luminous efficacy	Medium	Low	High	High	High
Luminance	< 200 cd/m² (full color) < 2000 cd/m² (green color)	1500 cd/m² (full color)	~ 10^5 cd/m² (full color) ~ 10^7 cd/m² (blue/green)	~ 1000 cd/m² (full color)	~ 1000 cd/m² (full color)
Contrast ratio	100: 1 (intrinsic)	Very high >10,000:1	Very high >10,000:1	High	High
Response time	ms	ms	ns	ms	ms
Operating temperature	0 to 60 °C	-50 to 70 °C	-100 to 120 °C	To be determined	NA
Shock Resistance	Low	Medium	High	Medium	Medium
Lifetime	Medium	Medium	Long	Medium [limited by MEMS]	Short [limited by LDs]
Cost	Low	High	High	High	High

Table 1: **Comparison among various technologies for displays.** Reproduced from J. Day, J. Li, D.Y. C. Lie, C. Bradford, J. Y. Lin, and H. X. Jiang, "III-Nitride full-scale high-resolution microdisplays," Appl. Phys. Lett. 99, 031116 (2011). doi:10.1063/1.3615679 and "Full-Scale Self-Emissive Blue and Green Microdisplays Based on GaN Micro-LED Arrays," Proc. SPIE 8268, 82681X (2012); invited. doi:10.1117/12.914061. H. X. Jiang and J. Y. Lin, "Nitride micro-LEDs and beyond – a decade progress review," Optics Express 21, A475 (2013) (invited), doi:10.1364/OE.21.00A475. AR needs brightness around 100,000 nits, according to LG Display. MicroLEDs have a pixel per inch (PPI) of 5,000 with 10^5 nits, compared to 3,500 PPI and ≤ 2 × 10^3 nits for OLEDs. AR also needs high operating speed.

cause damage to neurons or cells. MicroLEDs will play an important role in visible light communication, Li-Fi, to address the shortcomings of current 5G technologies.

LED professional: What obstacles does the research address? What about controllability, lifetime, or maintenance?

J.Y. LIN, H.X. JIANG: Large-scale microLED TVs showcased by Sony, Samsung and others have further demonstrated the superior performance of mircro-LED displays with no issues in controllability, lifetime, or maintenance. With the method of combining many modules, there is no limit in terms of achievable size of the microLED flat panel displays and TVs. However, as of today, even with the modular approach, the price of these products is still beyond having a mass market appeal. To manufacture these microLED TVs, a mechanical method has been employed to transfer millions of microLED pixels from III-nitride blue/green and AlGaInP red wafers to a large flat surface for providing electrical and control circuit connections to each microLED pixel of the display. How to improve the efficiency of this transfer process is one of the remaining keys to further improve yield and bring down the cost of microLED large flat-panel displays and TVs. Nevertheless, in our opinion, there are no fundamental material issues remaining in the field of microLED large TVs and flat panel displays.

LED professional: What's the current status of the developments for high-resolution displays? In which parameters can displays be improved?

J.Y. LIN, H.X. JIANG: For the developments of high-resolution microdisplays, the most critical issue is to realize a true full-color format. Unlike large microLED TVs, in which the three R-G-B color pixels can be placed side-by-side with a relatively large distance between them, the R-G-B color pixels must be arranged very closely or vertically stacked to provide a high spatial resolution. This will require either an approach to monolithically integrate III-nitride MQWs emitting R-G-B colors via epitaxial growth or integration between III-nitride blue/green and AlGaInP red wafers. Achieving III-nitride LED wafers emitting red color with high efficiency remains a big challenge for the community. However, a lot of progress has been made recently. Regarding microdisplays, on the fundamental level, there has not been much progress since our demonstration in 2009 of the first active matrix driving full-sale high-resolution (640 × 480 pixels) monochrome (blue/-green) microdisplay via hybrid integration with Si CMOS IC.

LED professional: What are the dominant challenges on the way to mass-produced displays based on microLEDs?

J.Y. LIN, H.X. JIANG: Large flat panel displays and TVs still face challenges of low yield and high cost. For microdisplays, the community needs to demonstrate a full color microdisplay, which can deliver all the expected advantages beyond current existing technologies such as LCD and OLED.

LED professional: Full-color microLED displays are challenging to achieve due to the lack of red InGaN devices. What are the latest research and findings in this field?

J.Y. LIN, H.X. JIANG: Several groups have made significant progress recently in achieving red and amber color InGaN LED wafers. We believe that the collective efforts by the community will overcome this material challenge. The next challenge is to demonstrate integration of three-color InGaN pixels and control electronics to achieve a full color microdisplay.

LED professional: What are the significant trends that drive the microLEDs research and developments?

J.Y. LIN, H.X. JIANG: Samsung, Sony and other companies started to sell microLED large flat panel displays and TVs. The significant trends that drive the microLED research and developments are their potential applications in wearable displays, smart phone displays, and AR/VR displays. We believe that III-nitride semiconductor microLEDs and

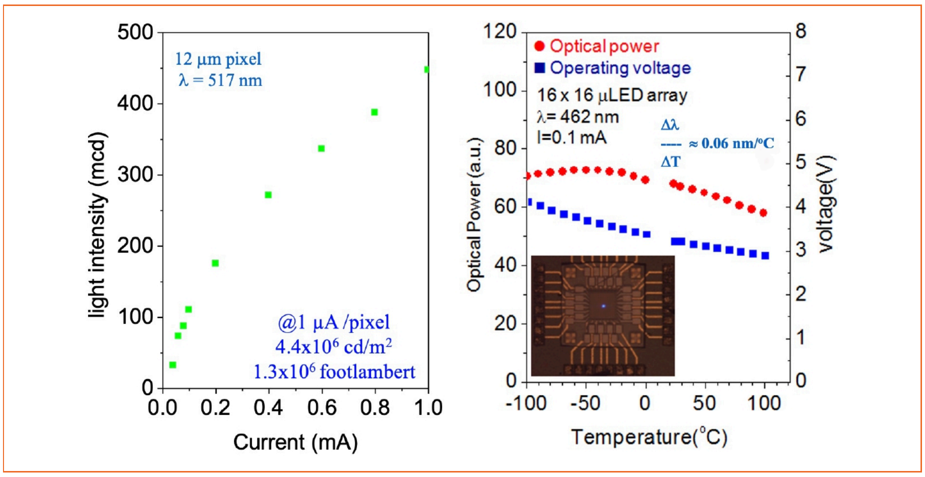


Figure 5: **Demonstration of ultra-high brightness and high temperature capability of III-nitride microLED:** (**left**) Luminance of a single green (517 nm) µLED pixel as a function of driving current and (**right**) the temperature dependence of the relative emission optical power of an InGaN microLED array. Reproduced from J. Day, J. Li, D. Y. C. Lie, C. Bradford, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. 99, 031116 (2011).

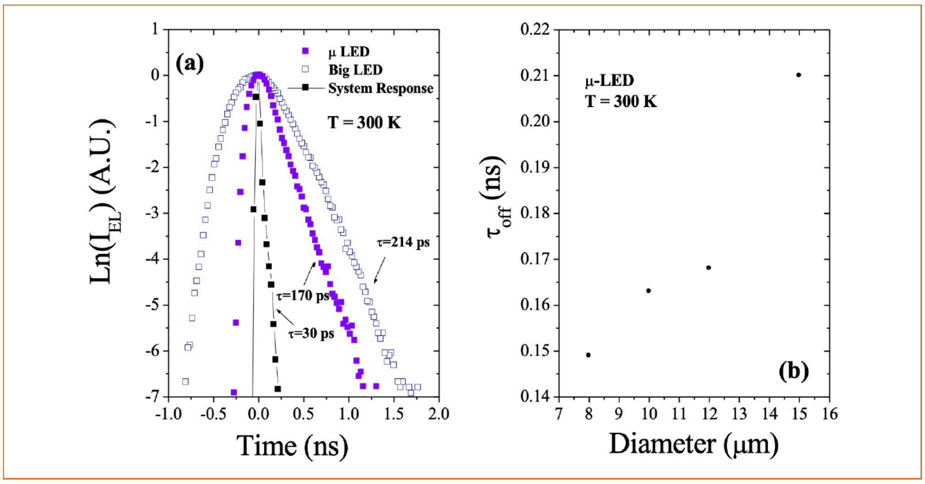


Figure 6: **Demonstration of fast operating speed of microLEDs:** (**a**) Transient responses of a microLED of 12 µm in diameter and a conventional broad-area LED (300 micron × 300 micron) and (**b**) the size dependence of the turn-off time, toff, of µLEDs. Reproduced from S. X. Jin, J. Shakya, J. Y. Lin, and H. X. Jiang, Appl. Phys. Lett. 78, 3532 (2001).

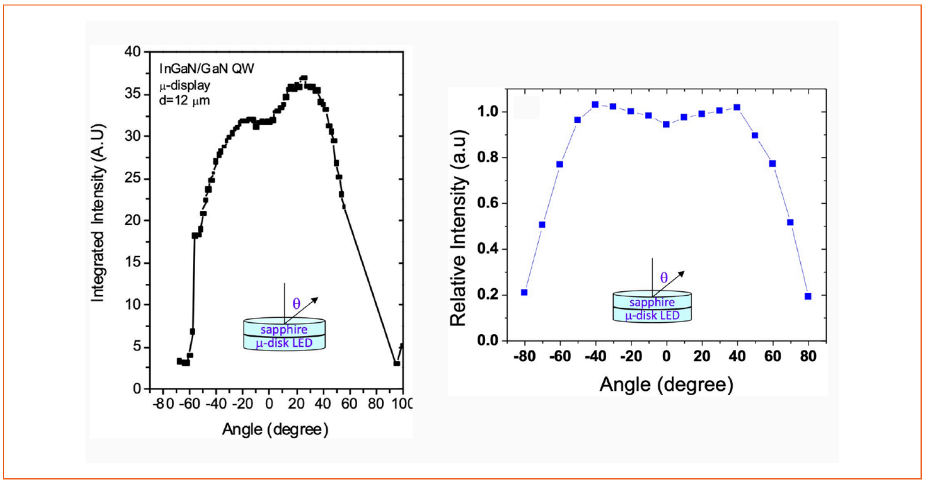


Figure 7: **Demonstration of large view angle of microLEDs: Viewing angle of microLEDs.** (**left**) Reproduced from H. X. Jiang, S. X. Jin, J. Li, J. Shakya, and J. Y. Lin, "III-Nitride Blue Microdisplays," Appl. Phys. Lett. 78, 1303 (2001). doi: 10.1063/1.1351521. (**right**) Viewing angle of microLEDs. Reproduced from H. X. Jiang, S. X. Jin, J. Li, J. Shakya, and J. Y. Lin, "III-nitride blue microdisplays," Appl. Phys. Lett. 78, 1303 (2001) and Z. Y. Fan, H. X. Jiang, and J. Y. Lin, "III-nitride micro-emitter arrays: development and applications," J. Phys. D: Appl. Phys. 41, 094001 (2008).

microdisplays will ultimately fulfill the new vision of metaverse.

LED professional: Recently, your work has been awarded by the International Solid-State Lighting Alliance. Congratulations! Where will your microLED journey lead you during the next five years?

J.Y. LIN, H.X. JIANG: As you probably know, our earliest patents on the microLED invention have application dates in 2000. The company, III-N Technology, Inc., founded by the both of us still holds key patented technology on an active matrix driving microdisplay via hybrid integration with Si CMOS IC and a full color microdisplay approach[1 2].
As this approach is now regarded as an industrial standard, we believe that there will be opportunities for us to collaborate with the "metaverse" industry for commercializing microdisplays. Currently, we are also making an effort to develop microLED related optical phased arrays for many different applications. In terms of III-nitride materials development, we are devoting a substantial amount of hard work in developing hexagonal BN ultra-wide bandgap semiconductor materials and have recently achieved BN thermal neutron detectors with a record high efficiency among solid-state neutron detectors.

LED professional: Thank you very much for taking us on this exciting microLED journey and giving us a glimpse into your extensive research work in this field.

J.Y. LIN, H.X. JIANG: We wish to thank LED Professional for the opportunity to give this interview. ■

References

[1] https://en.wikipedia.org/wiki/MicroLED
[2] https://www.depts.ttu.edu/ece/Nanophotonics/
[3] https://www.depts.ttu.edu/ece/faculty/hongxing_jiang/index.php
[4] https://www.depts.ttu.edu/ece/faculty/jingyu_lin/index.php

TOC Image: An embodiment of a full color microdisplay via vertically stacked RGB color pixels. (**left**) The schematics of AlGaInP and InGaN hybrid layer structure with tunneling junctions and circuit diagram showing the RGB pixel with VC as the common ground, and VR, VG, VB for red, green, and blue pixel control, respectively. (**right**) Illustration of utilizing a Si CMOS-compatible oxide-to-oxide aligned wafer bonding process to integrate the microdisplay with Si IC driver/processor as the backplane to provide a high density microdisplay. Reproduced from US patent #8,058,663 (Courtesy of III-N Technology, Inc.).

[1] "CMOS IC for micro-emitter based microdisplay" US patent 9,047,818 (Priority date: 03/23/2009; filed: 03/12/2011; issued date: 06/02/2015).
[2] "Micro-emitter array based full-color microdisplay" US patent 8,058,663 (Priority date: 09/26/2007; filed: 09/26/2008; issued date: 11/15/2011).

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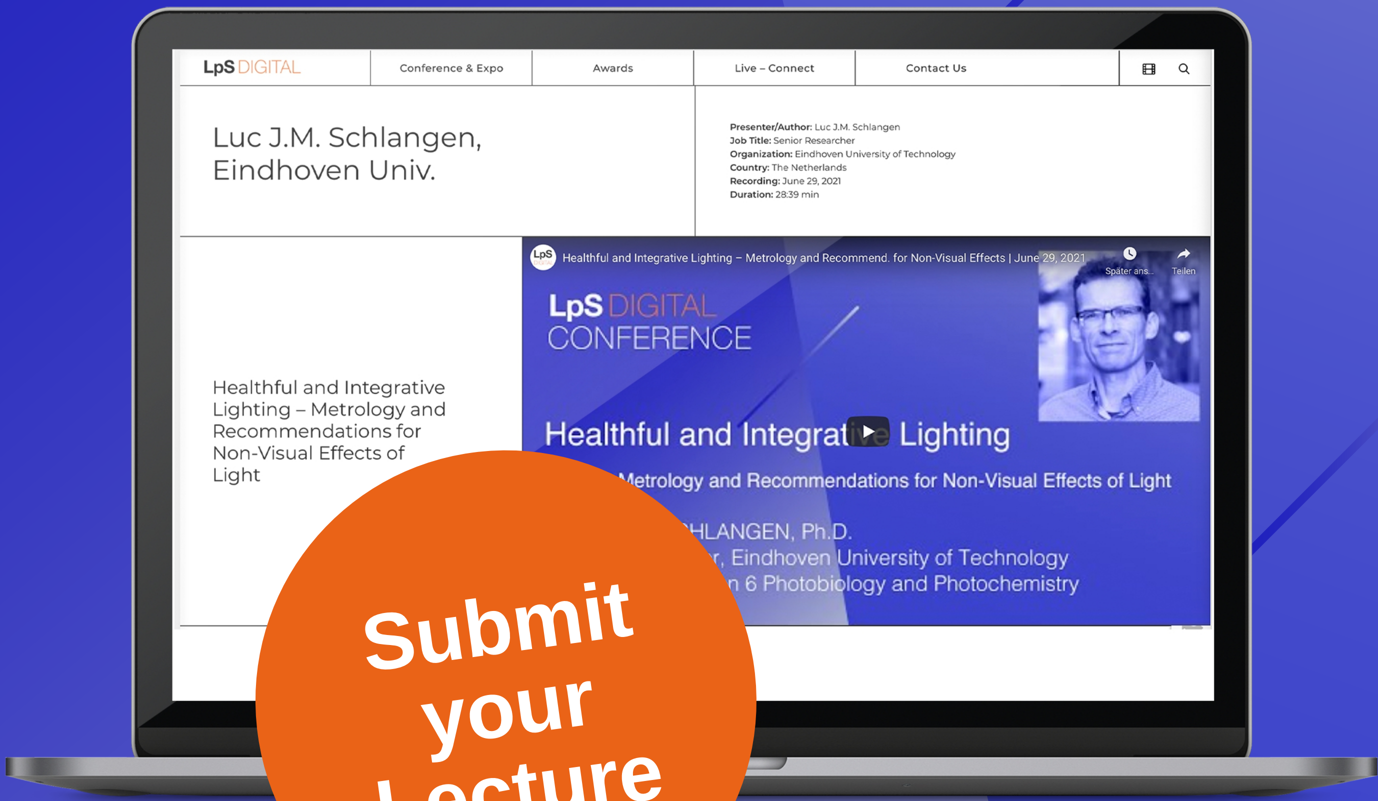

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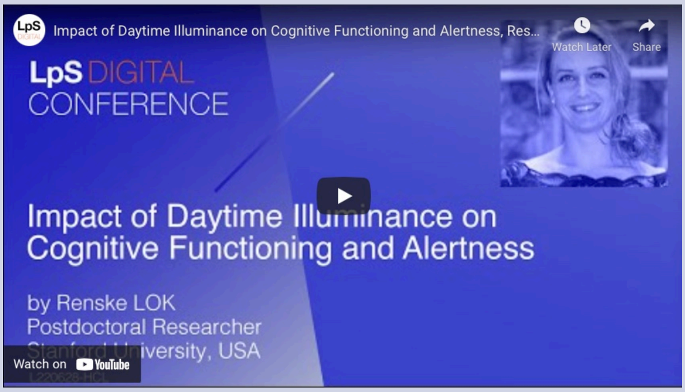
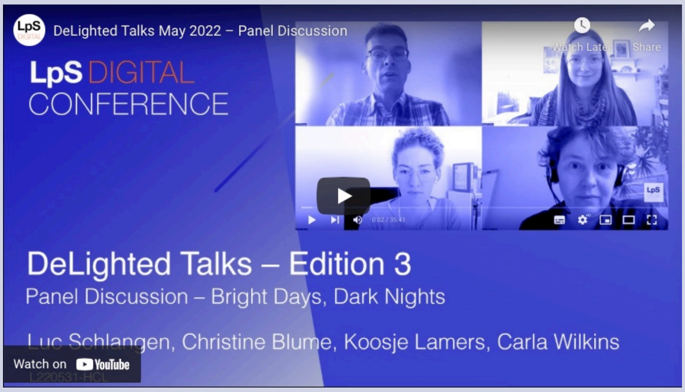
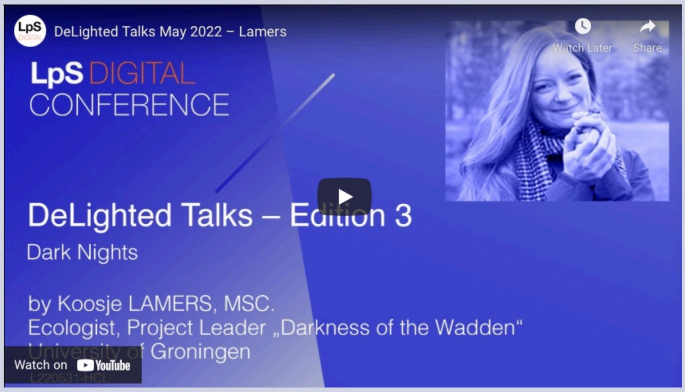
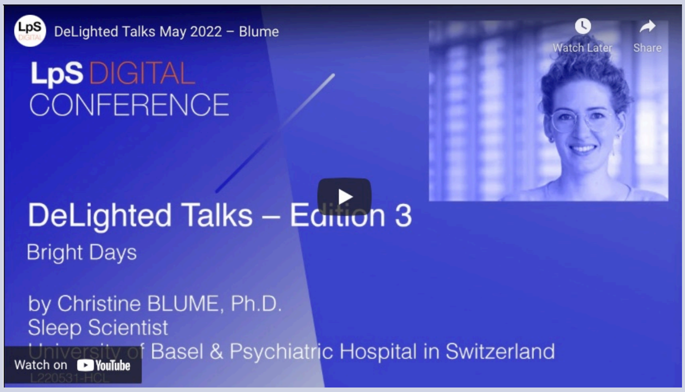








Changzhou Culture Plaza

Lichtvision Design

With multiple museums, a library and other service facilities, the Changzhou Culture Plaza is the cultural highlight of the newly created Changzhou city center. The six independent pavilions cantilevers over the open public space in the center of the site. A watercourse flows through the 17-hectare site, linking the various facilities together. Using high poles around the complex, Lichtvision emphasizes the visual coherence from the six 50-meter-high pavilions' façade. Linear underwater lighting highlights the watercourse for the retail and restaurant patrons. Additional linear and recessed ground luminaires provide accent lighting at trees, sculptures, benches, and handrails. Additional pole lights give general lighting along the pedestrian paths and other traffic routes.

The Changzhou Culture Plaza is embedded in a park in the new city center of the Chinese megacity Changzhou. In the basement of the six buildings there are retail areas and restaurants. On the floors above, exhibition areas, museums (including a science and technology museum) and a library form the cultural core of the plaza.

The special feature of the 363,715 square meter building complex is its sculptural architecture: six, free-standing pavilions cantilevering upwards in large arches, creating an expansive, segmented roof. At the base, each pavilion's volume decreases on two sides, opening up a covered public space that merges into the surrounding park on all sides. A watercourse flows through the 17-hectare site and connects the each pavilion. Daylight comes through the openings between the pavilions and reaches the shops, restaurants, and the watercourse in the basement.

Working with both gmp Architekten and the landscape architects at WES, Lichtvision had to fulfil the façade and public space lighting according to the architect's conceptual approach while also creating the atmosphere around the watercourse and landscape desired by the landscape architect.

Façade lighting emphasizes the sculptural appearance

One challenge to the façade lighting was the sheer size of the architecture. Each individual pavilion rises 50 meters into the air. Although each building serves different functions on the inside, they are intended to form a singular, coherent, architectural unit on the outside. Uniform façade lighting emphasizes this very unity. Using high pole lights around the complex, Lichtvision is able to carry out this design intent. The homogeneous floodlighting emphasizes the sculptural appearance of the pavilions and their cantilevered structure. Poles were also used for the general lighting of the streets and pedestrian areas. To distribute the light optimally and to enhance zoning and orientation, higher poles highlight the spatial axis, while lower poles accentuate the entrance areas around the plaza. From the cantilever edges, the central public space between the pavilions is illuminated creating a meeting point and inviting passersby to take a break. Façade details are emphasized by linear light that blends into the architecture. Additionally, white and colored lights are integrated into the horizontal slats of all inward-facing façades.

Water features in linear light

Natural daylight highlights the water during the day. Underwater linear lights illuminate the waterfront, water features, cascades, and the water basin at night. The artificial lighting visually enhances the water on the riverside promenade. Other distinctive elements such as trees and sculptures are illuminated by recessed floor luminaires. Linear luminaires are integrated into benches and handrails. At night, the lighting design sets the scene for the architectural features and natural elements. The lighting concept reinforces the architectural unity of the pavilions and makes the cultural center appear as if it were radiating from within.

Typology: Culture Center / Museums & Mixed-Use
Scope of Work: Landscape and facade lighting
Completion: 2020
Location: Changzhou, China
Size (GFA): ≈ 350 000 m^2

Client: Changzhou Jinling Investment and Construction Co., Ltd.
Project Lead: Lichtvision Design; Raoul Hesse (PM) and Ying Chien
Architect: gmp International GmbH
Planning Partners: WES LandschaftsArchitektur GmbH
Photographer: © Schran Images

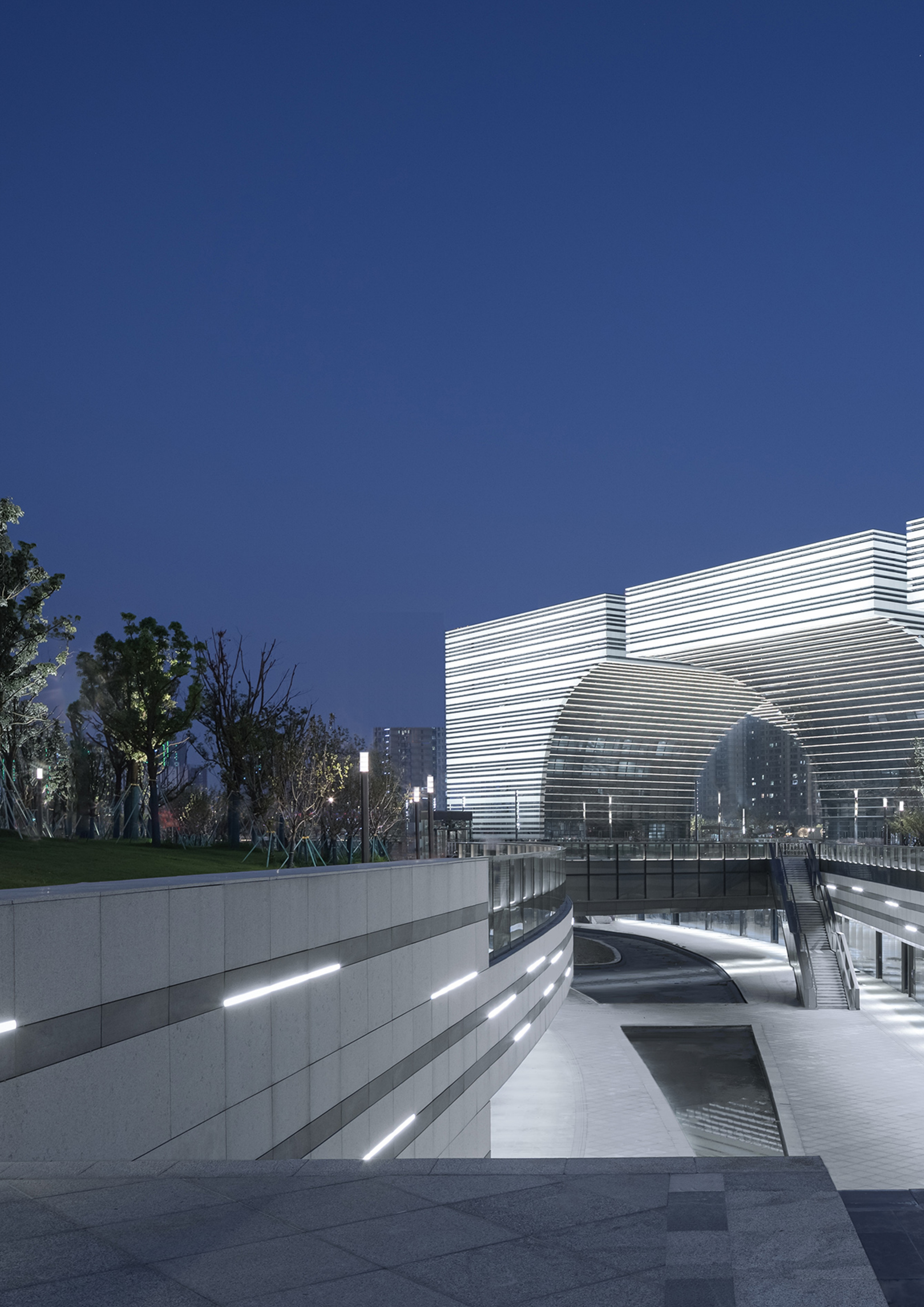
Project Link:
https://www.lichtvision.com/projects/museums-cultural-instiutions/changzhou-culture-plazachangzhou-china.html

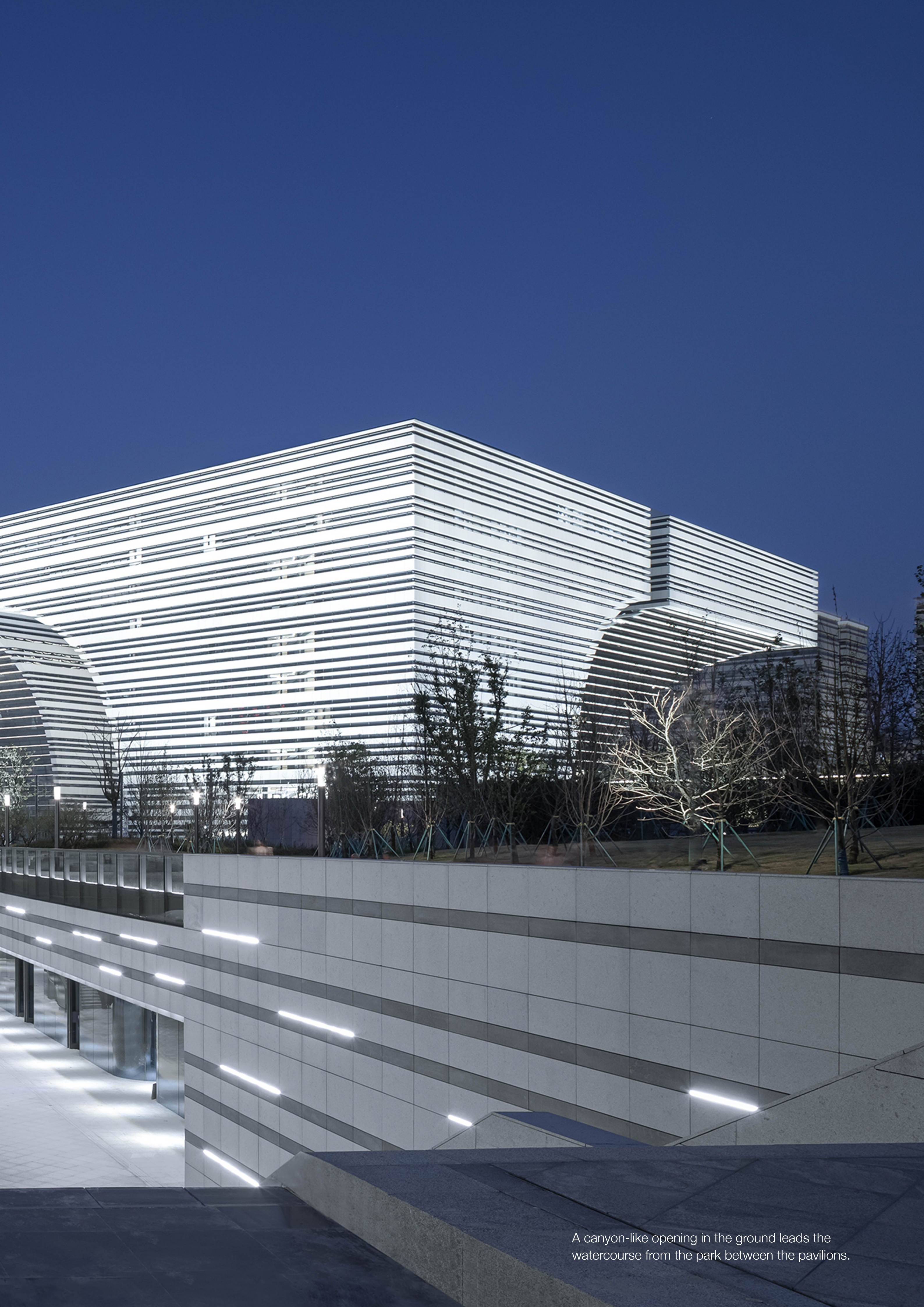
http://www.lichtvision.com

LICHTVISION DESIGN

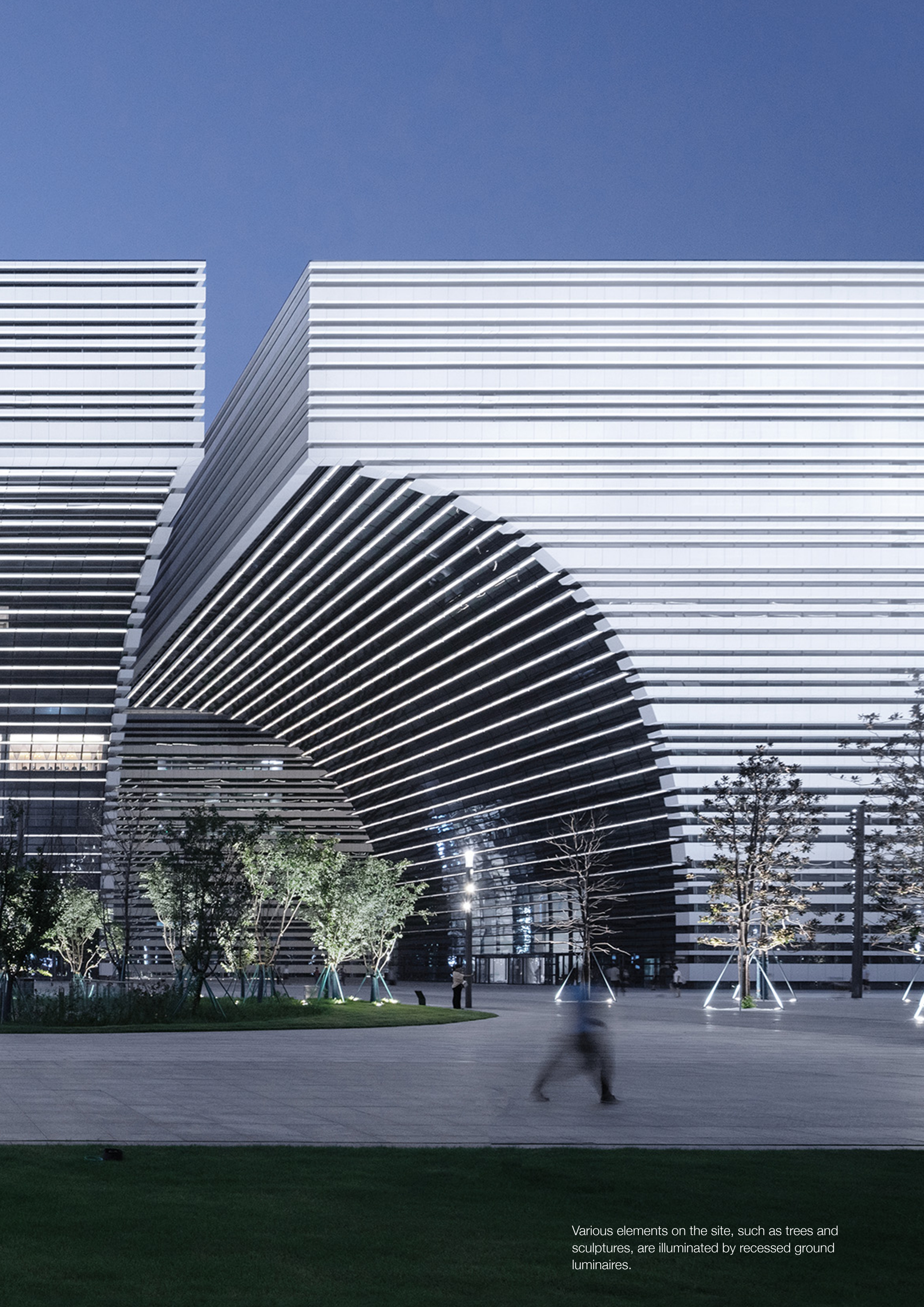
Using high poles around the complex, the façade lighting emphasizes the architecture’s visual unity.

At night, the lighting design sets the scene for the architecture features of the cultural center, visible from afar.





A canyon-like opening in the ground leads the
watercourse from the park between the pavilions.



Various elements on the site, such as trees and sculptures, are illuminated by recessed ground luminaires.

Development of microLED

Professor Jingyu LIN & Professor Hongxing JIANG, Department of Electrical and Computer Engineering, Texas Tech University, Lubbock, Texas 79409, USA

This perspective provides an overview of early developments, current status, and remaining challenges of microLED (μLED) technology, which was first reported in Applied Physics Letters in 2000 [S. X. Jin, J. Li, J. Z. Li, J. Y. Lin and H. X. Jiang, "GaN Microdisk Light Emitting Diodes," Appl. Phys. Lett. 76, 631 (2000)]. Today, microLED is recognized as the ultimate display technology and is one of the fastest growing technologies in the world as technology giants utilize it on a wide range of products from large flat panel displays and televisions, wearable displays, and virtual reality displays to light sources for the neural interface and optogenetics. It is anticipated that the collective R&D efforts worldwide will bring microLED products not only to the mass consumer electronic markets but also to serve society on the broadest scale by encompassing sectors in medical/health, energy, transportation, communications, and entertainment.

It is fascinating to witness that a change in the format of light emitting diodes (LEDs) from a standard size of 300 μm × 300 μm for indicators and 1 mm × 1 mm for power LEDs for lighting [1,2] to a micro-size of ≈ 10–30 μm [3–7] has created a sub-field in III-nitride and display research and launched intensive efforts in the development of emerging III-nitride devices and products [8]. The huge opportunity in consumer electronics is the major driving force behind the recent developments of innovative technologies and products based on micro-size LEDs (or microLEDs). According to MarketWatch, "The global MicroLED market is valued at $170 million in 2018 and is expected to reach $17 billion by the end of 2025, growing at a compound annual growth rate (CAGR) of 78.3% during 2019–2025" [9]. To further illustrate the growth of this sub-field within the III-nitride and display fields, **Figure 1** plots the number of publication items related to "microLEDs" or "micro-size LEDs" for the years from 2000 to 2019 via the Google Scholar search. The plot displays a typical growth of a fresh field, which in this case began in 2000 with a gradual growth until 2005. Beginning in 2006, the field experienced an exponential growth with a total of nearly 3000 publication items in 2019. The R&D activities most likely are not yet peaking off, and the growth is expected to continue for a while since many researchers believe that the opportunities created by the microLED technology will be too massive to miss. Currently, "almost all the big names in the tech industry see MicroLEDs as the next big thing," [10] and researchers are racing to overcome the key technical barriers to bring microLED products to the market. Emerging microLED products include wearable displays for high speed three-dimensional/augmented reality/virtual reality (3D/AR/VR) display applications, high brightness/contrast large flat panel displays and TVs, and light sources for the neural interface and optogenetics and for visible light communications (Li-Fi).

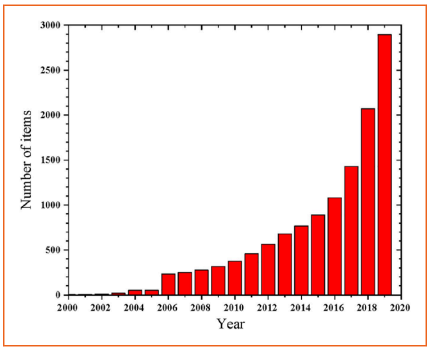


Figure 1: Plot of publication items related to microLED or micro-size LED vs years from 2000 to 2019 via the Google Scholar search.

The inception of the microLED concept was [3–7] during the period of the emergence of blue/white LED based solid-state lighting after the invention of III-nitride blue LEDs in the early 1990s [11–13]. It was well known from the traditional III–V semiconductors that optoelectronic devices, including emitters and detectors with microcavities, possess unique advantages such as low power consumption, high quantum efficiency, enhanced speed, reduced lasing threshold, ability of miniaturization and 2D array integration, and reduced cost [14–16]. Various III-nitride microstructures, including micro-disks, rings, pyramids, prisms, waveguides, and optically pumped vertical cavity surface emitting lasers (VCSELs), have been successfully fabricated by different research groups prior to 2000 [17–29]. Enhanced quantum efficiencies, optical resonant modes, and optically pumped lasing actions were observed in GaN micro-disks, rings, pyramids, and GaN VCSEL structures [17–28].

The question naturally arises: What features will a micro-sized blue/green LED and array have? Although the device architecture of microLED itself is much simpler than that of a VCSEL [14], back then, we faced two major technical challenges for realizing blue/green μLEDs [29]. The first problem was the relatively poor p-type conductivity due to the known large Mg acceptor energy level of about 160 meV in GaN, [1,11–13] which becomes more severe as the LED size scales down to about 10 μm. The second issue was that the ratio of the etched region to the active area increases with a decrease in the μLED size, which tends to enhance the non-radiative recombination of injected electrons and holes due to plasma etching induced damage [30] to the sidewalls of μLEDs. These two issues were overcome to some extent, and we were able to inject current into μLEDs to generate intense blue emission [3–7]. The results of the first μLED and μLED array based on InGaN quantum wells (QWs) are summarized in **Figure 2**, **Figure 3** which illustrates a μLED array fabricated on a single InGaN LED wafer. The SEM image shown in **Figure 2**(b) reveals that this first μLED array has a pitch of 50 μm and a μLED pixel size of 12 μm in diameter with a Ni/Au p-contact of 10 μm in diameter. **Figure 2**(c) illustrates a blue μLED in action under current injection, whereas **Figure 2**(d) shows a conventional blue LED with a size of 300 μm × 300 μm in action for comparison.

A natural subsequent step was to implement various schemes to address μLEDs within a μLED array to create practical devices. Very quickly, many potential applications started to emerge for μLEDs and arrays. One example is an interconnected μLED with enhanced emission efficiency over the conventional LEDs of the same device area [4]. Another example is by connecting a number of μLEDs in series so that the sum of the voltage drop across the individual μLEDs adds up to the voltage of a high voltage AC or DC supply to create a single-chip high voltage AC/DC-LED to match the infrastructure for lighting [31–33]. As of today, GaN high voltage single-chip AC/DC-LEDs have been widely commercialized for general illumination and for automobile headlights. The third example is a µLED array with independently addressed pixels or microdisplay (µdisplay), which was first introduced by the authors' group in between 2000 and 2001 [5,6]. To demonstrate the concept, a 10 µm × 10 µm array (with a pixel size of 12 lm) passive driving "µdisplay" was first demonstrated, which is capable of only displaying characters [6]. Around the same time, it was shown that µLEDs have a sub-nanosecond response time [7]. Several groups were engaged early in the development of µLED technology and its applications [34–43]. For instance, the concepts of MicroLEDs for Li-Fi and medical applications were pursued early on [34–40]. A matrix-addressing scheme was developed to demonstrate a passive-matrix microdisplay with 128 × 96 pixels [35]. The concepts of flip-chip bonded microdisplays and µLEDs on Si substrates have also been developed [41–43].

The real breakthrough in µLED displays was achieved in 2011 by the authors' group by demonstrating full-sale high-resolution (640 × 480 pixels in Video Graphics Array or VGA format) monochrome blue and green microdisplays capable of delivering video graphics images using an active matrix driving scheme [44–46]. The challenge for achieving µLED based µdisplays with active driving is that III-nitride µLEDs cannot be fabricated directly over Si IC circuitry. To achieve an active driving scheme, a hybrid µdisplay concept was adopted. The microLED array was heterogeneously integrated with a CMOS active matrix driver via flip-chip bonding using indium metal bumps [44–48], as shown schematically in **Figure 3**(a). A microdisplay controller CMOS active matrix with 640 × 480 pixels with a controllable current from 0.5–10 µA per pixel has been designed and fabricated in a CMOS process [44–48]. **Figure 3**(b) shows an image of a packaged flip-chip bonded actively driven microdisplay. This microdisplay has 640 × 480 pixels in a VGA format with a µLED pixel size of 12 µm in diameter and 15 µm in pitch or 1667 pixels per inch (ppi). **Figure 3**(c) shows a green µdisplay in action with its size relative to a US quarter and displays a video graphic image of a leopard in **Figure 3**(d). Each green µLED pixel outputs roughly 1 mcd/µA, and the luminance increases almost linearly with driving current (*I*) for $I < 100$ µA. For the µdisplay shown in **Figure 3** with a pitch distance of 15 µm, when every pixel within the array is lit up and operates at 1 µm, the brightness of the µdisplay is several orders of magnitude higher than those of liquid crystal displays (LCDs) and organic LEDs (OLEDs) [44–48]. The µLED microdisplay also has an outstanding thermal stability. The emission intensity of the µLED emission decreased only by about 10% when the operating temperature was raised from room temperature to +100 °C and remained almost constant when the temperature was cooled down from room temperature to −100 °C, while the operating voltage at 0.1 mA decreased from 4.1 V at −100 °C to 2.9 V at +100 °C due to increased free holes and improved p-type conductivity of the p-layer with increasing temperature [44]. Moreover, µLEDs have a "turn-off" speed on the order of 0.2 ns [7].

Though the first active matrix driving µLED microdisplay capable of video graphics image delivery is monochromatic (blue or green) [44–48], it demonstrated the validity of the µLED technology. It possesses outstanding characteristics as a display in comparison with other technologies such as LCD and OLED displays, including high brightness, efficiency, speed, high thermal stability, and contrast [44–48]. These exceptional features were quickly

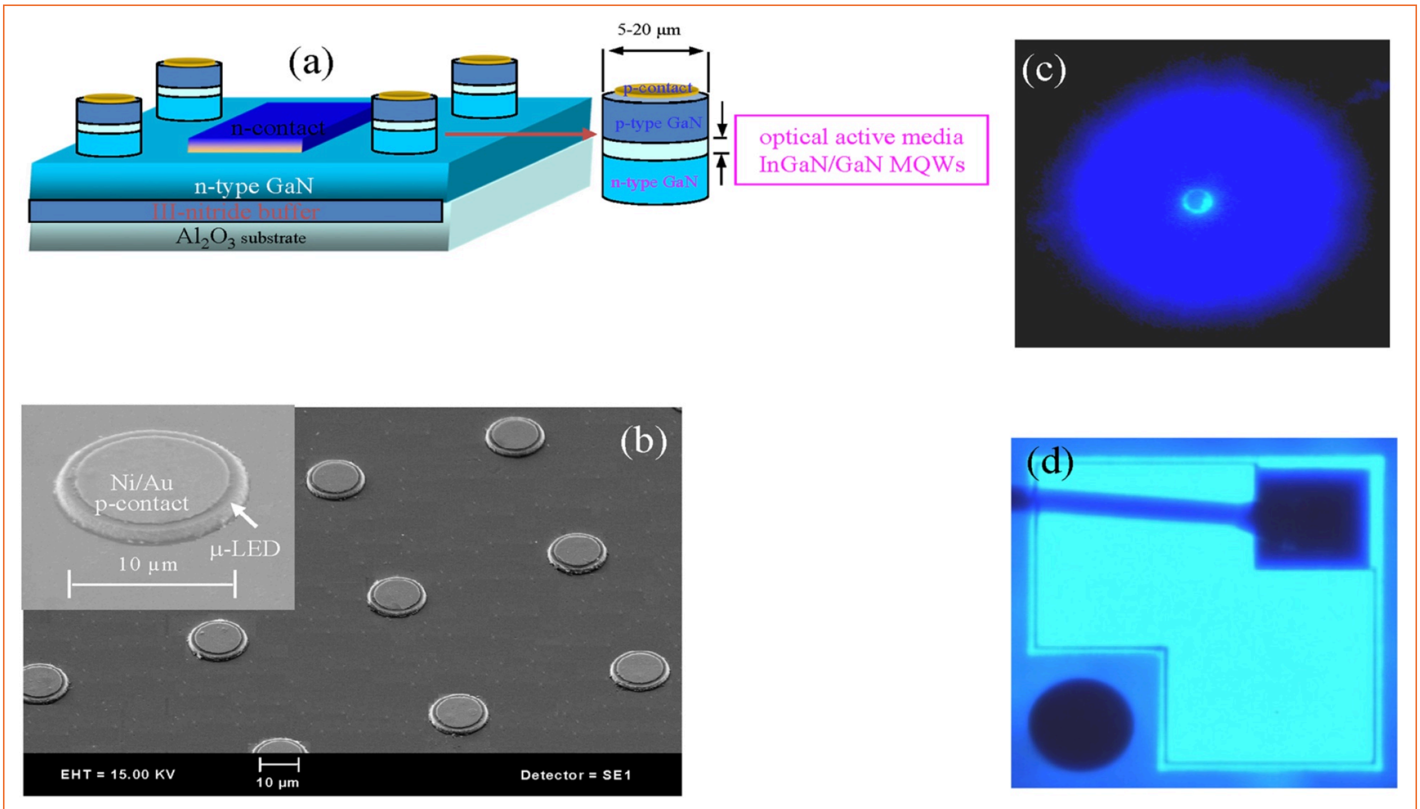


Figure 2: The first current injection microLED based on p-GaN/InGaN/n-GaN QWs. (**a**) Schematic layer structure diagram of an InGaN/GaN QW microLED (µLED) array. (**b**) SEM image of an InGaN/GaN QW µLED array with a µLED pixel diameter of 12 µm and a *p*-type Ni/Au contact diameter of 10 µm. (**c**) Optical image of a blue µLED in action. (**d**) Optical image of a conventional blue LED (0.3 mm × 0.3 mm) in action for comparison. Reproduced from Jin et al., Appl. Phys. Lett. 76, 631 (2000). Copyright (2000) AIP Publishing.

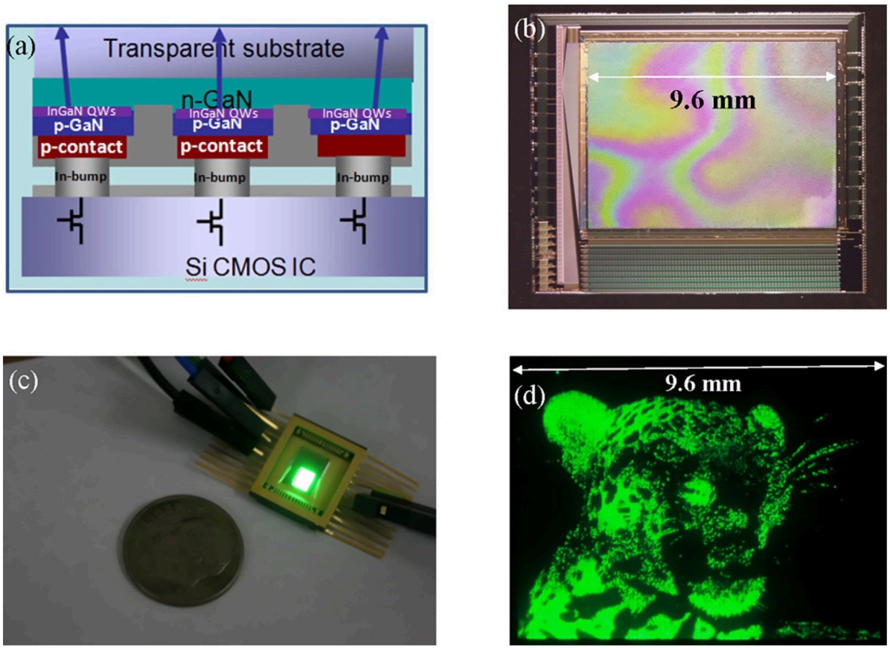


Figure 3: The first monochromatic (blue or green) full-scale InGaN/GaN QW microLED microdisplay in the VGA format (640 × 480 pixels) capable of playing video graphics images. (**a**) Illustration of flip-chip bonding between the µLED matrix array and CMOS driver IC via indium bumps to form a highly integrated microdisplay in one package. Reproduced from Day et al., Appl. Phys. Lett. 99, 031116 (2011). Copyright (2011) AIP Publishing; (**b**) Optical microscopy image of a packed VGA InGaN/GaN QW microdisplay. Reproduced from Day et al., Appl. Phys. Lett. 99, 031116 (2011). Copyright (2011) AIP Publishing. (**c**) A fully assembled InGaN/GaN QW microdisplay (having 640 × 480 pixel with a pixel size of 12 µm and a pitch distance of 15 µm) operating at a driving current of 1 µA per pixel, with its size relative to a US quarter. Reproduced from Day et al., Proc. SPIE 8268, 82681X (2012). Copyright (2012) SPIE. (**d**) A grayscale projected image of a leopard from a green VGA InGaN/GaN QW microdisplay (having 640 × 480 pixels with a pixel size of 12 µm and a pitch distance of 15 µm) operating at a driving current of 1 µA per pixel. Reproduced from Day et al., Proc. SPIE 8268, 82681X (2012). Copyright (2012) SPIE.

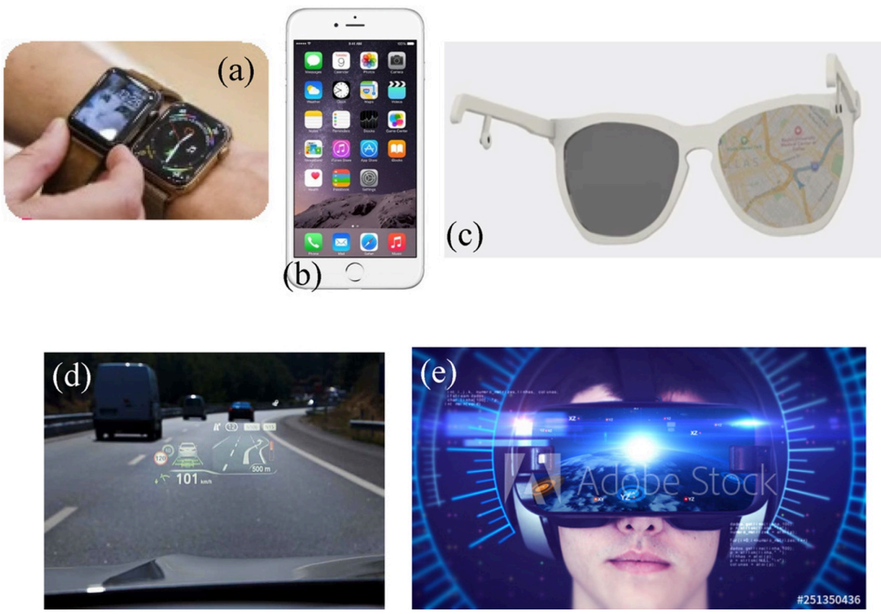


Figure 4: Potential applications of microLED microdisplays for (**a**) smart watches [credit: Apple], (**b**) smart phones [credit: Apple], (**c**) i-glasses [credit: Apple], (**d**) dashboard and pico-projectors [credit: Fabian Kirchbauer; BMW AG], and (**e**) 3D/ AR/VR displays [credit: Yucel Yilmaz, Adobe Stock].

recognized as important advantages for next generation displays. **Figure 4** summarizes potential applications of µLEDs, that are currently under intensive pursuits by almost all the big names in the tech industry for (a) smart watches, (b) smart phones, (c) i-glasses, (d) dashboard- and pico-projectors, and (e) 3D/AR/VR displays. In particular, the sub-nanosecond response of µLEDs has a huge advantage over other display technologies for 3D/AR/VR displays since these devices need more images, more pixels per image, more frames per second, and fast response **[49]**.

After the demonstration of the first VGA monochrome µLED microdisplay **[44–48]**, substantial progress has been made in the development of monochromatic µLED microdisplays with higher pixel density, smaller pixels, and larger display size **[50–53]**. However, the most important next step for µLED microdisplays is the realization of a full color microdisplay. Different approaches to the pursuit of full color include (a) quantum dot (QD) color conversion **[54–57]**, (b) nanowire microLEDs **[58–60]**, and (c) combination of three monochromatic red, green, and blue µdisplays based on AlGalnP (red) and GaN (green and blue) materials **[61]**.

However, these approaches face different challenges such as low convention efficiency and cross talk for QD color conversion, are difficult to integrate nanowire wafers with driving circuits, and are difficult to integrate µdisplays with an optical control system for the combination of three µdisplays. Therefore it remains to be seen which method will eventually succeed. We believe that this is a remaining area where academic researchers can still make important contributions.

Another area in which µLEDs can make a large impact is in medical applications **[38–40] [62–71]**. **Figure 5** shows the illustrations of (a) a µLED array implanted inside a rat for neutron stimulation with wireless control;68 (b) µLED based multi-shank optogenetic neural probes that can provide spatially confined optical stimulation of simultaneously monitored neurons in behaving animals **[64]**; (c) I-LED for neural stimulation and optogenetics **[38–40]**, (d) µLED microdisplays to aid people who are blind or have sight loss **[69]**; and (e) µLEDs for optical cochlear implants to aid people with hearing loss **[66,70,71]**. The most important advantages of µLEDs for applications of neural stimulation/optogenetics are its ability of array formation, comparable size with neurons and high spatial resolution, and high speed in comparison with conventional LEDs, and they have a lower light intensity in comparison with a micro-laser, which may cause damage to neurons or cells.

The most significant progress made in μLED displays is in fact in the large flat panel displays and TVs. **Figure 6** illustrates several generations of such products demonstrated by large consumer electronics companies since 2012. The first large screen μLED TV was successfully developed by Sony in 2012, named Crystal LED display [72]. It has a total of 6.22 million μLED pixels (1920 × 1080 × 3). In comparison to LCD displays, it has 3.5 times higher picture contrast, 1.4 times better color range, a wider viewing angle of 180°, a lower power consumption of less than 70 watts, and better motion reproduction with 10 times faster response time compared to LCD models. Based on Sony's Crystal LED display, a mechanical method has been developed and used to transfer millions of μLED pixels from III-nitride blue/-green and AlGaInP red wafers to a large flat surface, which provides electrical and control circuit connections to each μLED pixel of the display.

Sony's large-scale μLED TV again demonstrated the validity of μLED technology and initiated a furious race in the display industry to bring μLED large flat panel display products to the global consumer electronic markets. Though with many outstanding features, the manufacturing yield of Sony's first generation large μLED TV could be problematic because the whole TV was built from a single panel of millions of pixels. As illustrated in **Figure 6**(b), when the next large μLED TV, a 146-in. μLED TV, showcased with the brand name of "The Wall" by Samsung in 2017 [73], it incorporates a method of combining an array of much smaller modules (or panels) to form a large flat panel display. This modular approach significantly improved the overall manufacturing yield since the yields for each module and for the final TV assembly are enhanced. It appears that the use of the modular approach has become

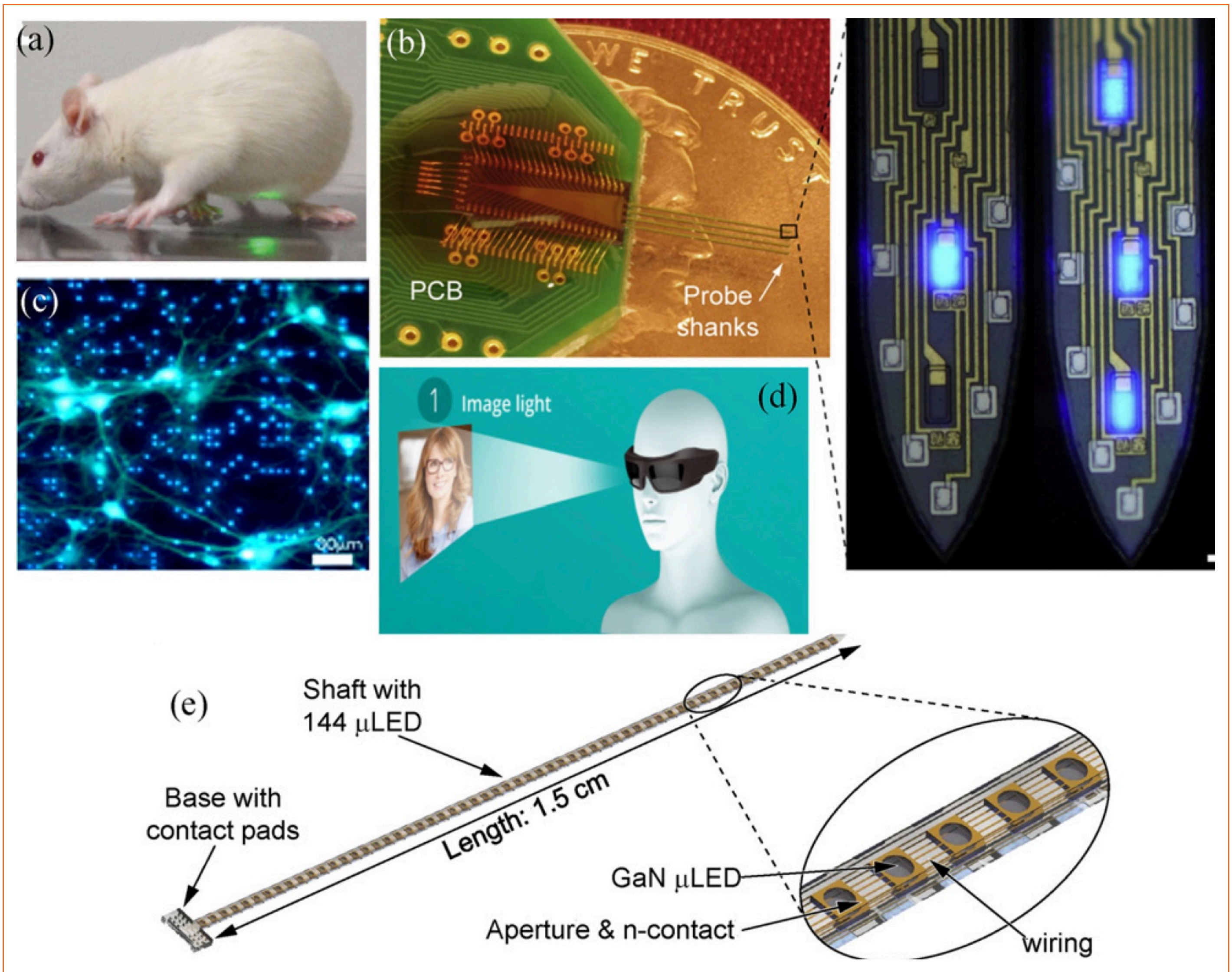


Figure 5: MicroLED for medical applications. (**a**) Rat implanted with a green μ-LED for optogenetic stimulation. Reproduced from Mickle et al., Nature 565, 361 (2019). Copyright (2019) Springer Nature. (**b**) μLED probe drives localized spiking in freely moving mice: photograph of an implantation-ready μLED probe on a penny and high- magnification images of the illuminated μLEDs (inset, scale bar, 15 lm). Reproduced from Wu et al., Neuron 88, 1136 (2015). Copyright (2015) Elsevier, Inc. (**c**) Neural cells expressing ChR2 are covered by a 64 × 64 matrix of the μLED array with individual control of their intensity and timing (inset, scale bar, 30 lm). Reproduced from Grossman et al., J. Neural Eng. 7, 016004 (2010). Copyright (2010) IOP Publishing. (**d**) μ-LED microdisplay aiding people who are blind or have sight loss. Reproduced from V. C. Coffey; Opt. Photonics News 29(4), 24–31 (2018). Copyright (2018) OSA. (**e**) Schematic of an optical cochlear implant probe comprising a probe base carrying contact pads and a 1.5-cm-long shaft comprising 144 μLEDs. Reproduced from Klein et al., Front. Neurosci. 12, 659 (2018). Copyright (2018) Klein, Gossler, Paul, and Ruther.

Figure 6: Evolution of MicroLED large flat panel displays and TVs: (**a**) first ILED TV of 55" "Crystal LED TV" produced by Sony in 2012 [credit: Sony]. (**b**) 14600 modular MicroLED TV "The Wall" showcased by Samsung in 2017 [credit: Samsung]. (**c**) An extremely large 16K (21 m × 5.5 m) MicroLED "Crystal LED TV" showcased by Sony in 2019 [credit: Sony].

an industrial standard for manufacturing large flat panel μLED displays and TVs. The most recent μLED large display showcased by Sony at the 2019 National Association of Broadcasters trade show in Las Vegas has a format of 16 K and a dimension as large as 21 m × 5.5 m, as illustrated in **Figure 6**(c). It still maintains all the outstanding features of μLEDs mentioned above. This recent progress clearly demonstrates that with the method of combining many modules, there is no limit in terms of size of the flat panel displays. However, as of today, even with the modular approach, the price of these products is still beyond having a mass market appeal. With the rapid progress made recently in this field, the question is no longer if they can but rather when they will penetrate mass markets for various applications. One thing to be cautious about is how large will the market demand for μLED flat panel displays and TVs actually be. With the existing OLED and QD LCD displays with good performances on the market at relatively low prices, it still remains to be seen if μLED flat-panel displays can dominate the mass consumer electronic markets as the "ultimate display" or just suit for some niche applications.

Looking forward, μLEDs appear to be particularly suitable for medical applications for the neural interface/optogenetics [38–40,62–71] and for LiFi [36,37,74–76]. There appear no genuine barriers to use μLEDs for these applications. Various μLEDs including different sizes, form factors such as μLEDs on flexible and curved surfaces [62–71], colors, and response speeds for different applications have already emerged. However, the efficiency of μLEDs tends to decrease with reducing size due to enhanced surface effects, and hence, one needs to take into consideration the trade-off between bandwidth, operating speed, and efficiency when designing optical systems for these applications [77].

On the other hand, μLED based microdisplays and large flat panel displays still face significant challenges. For μdisplays, the most critical issue is to realize a true full-color format. For μLED large flat panel displays, recent demonstrations of large TV and displays certainly revealed that in particular, designed tools and facilities for μLED mass transfer and assembly have been developed by a few large companies, and hence, there are no barriers from science and engineering perspectives. It appears that overcoming the manufacturing yield is more challenging than anticipated since it has been more than 7 years since the demonstration of the first μLED large TV (Crystal LED) by Sony in 2012. The μLED and μdisplay manufacturers need to develop their own specialized infrastructures and supply chains. All of these will take time to mature. In the academic arena, in our opinion, similar to the field of polymeric OLED displays [78], there is still a great deal of research opportunities to further develop innovative techniques for microLED transfer and assembly, such as laser-induced forward transfer or laser-based layer transfer [79–82], microtube technology [83], light-based debonding [84], transfer using a magnetorheological elastomer [85], chemical lift-off [86], transfer printing [87,88], and other techniques.

Despite the remarkable progress, many opportunities remain for taking advantage of improved understanding of the basic III-nitride material properties and growth/device processes to benefit the further development of the microLED technology. For instance, microLEDs are expected to operate at high current densities for many emerging applications. As such, more studies on the phenomenon of roll-over quantum efficiency (or efficiency droop effect) at high current densities, possibly due to Auger or Mg impurity band conduction effects in visible and UV LEDs [89–95], are needed for microLEDs. It is also well known that III-nitride LED structures grown on GaN bulk substrates exhibit more desirable characteristics over those grown on sapphire substrates. However, little work has so far been done on the fabrication of microLEDs on GaN and SiC bulk substrates. The utilization of such device structures [86–109] in comparison with those of microLED wafers grown on sapphire could provide useful insights into the effects of dislocation density on the efficiency of microLEDs and approaches for further reducing the leakage current density and enhancing p-type conductivity in microLEDs. Similarly, very little comparison works have been carried out on microLEDs fabricated from polar, semi-polar, and non-polar InGaN quantum wells. As such, the properties and performances of semi-polar or non-polar microLEDs are very scarce, but they are of high interest as these structures [77,110–116] are able to provide insights into the potential effects of strain and spontaneous polarization on the efficiency, operating speed, and optical polarization properties of microLEDs.

Another important aspect of III-nitride heterostructures and QWs is the polarization-induced doping, which has been widely exploited to improve p-type doping in III-nitride LEDs, lasers, and p-type field effect transistors [117–120], which however has yet to be explored in microLEDs for improved performance. Likewise, valuable insights can be gained from novel device architectures utilized to realize VCSELs, superluminescent LEDs, and micro-cavity lasers [121–127], such as tunnel junction intracavity contact [122], to further improve the characteristics of microLEDs. Furthermore, due to the lack of red InGaN wafers, realizing full color all III-nitride microLED microdisplays is exceedingly challenging, but it is highly desirable. InGaN nanowires and nanocolumn (NC) LEDs have shown promising results for full color microLED applications [58–60] [128–131]. Most recently, a 16 × 16 array of InGaN/GaN-based NC microLEDs with different emission colors has been attained monolithically via a one-step selective area growth, pointing to the potential of integrated NC microLEDs for realizing full-color microLEDs [131]. At the same time, approaches including funnel-tube array and projection lithography patterned QDs on microLED wafers have shown to provide improved conversion efficiencies and reduced cross talk [132,133]. On the other hand, the benefits of InGaN quantum dots (QDs) that have been extensively explored recently in blue and UV III-nitride wafers [134–138] and in nanowire based micro-emitters [139,140] have yet to be investigated for microLEDs. It will be interesting to investigate the characteristics of QD embedded microLEDs, as QDs are expected to inhibit non-radiative recombination channels and hence affect the quantum efficiency and the operating speed of microLEDs.

A recent interesting development is the growth of III-nitride on a two-dimensional (2D) or layer-structured template, and the utilization of this 2D template as a release layer for mechanical transfer of III-nitride-based devices [141–144], as a layer-structured material such as hexagonal boron nitride (h-BN), enables a natural separation of the active layer from the substrate to produce freestanding device structures [145–147]. The fabrication of microLEDs on 2D templates could potentially facilitate innovative techniques for microLED transfer and assembly and enable novel freestanding and flexible microcavity photonic devices, complementary to more established techniques for achieving flexible inorganic photonic/electronic devices [62–71] [87,88,148].

In summary, we see a very bright future for MicroLEDs. The most significant driving force is the potential huge market demand for this technology. The collective efforts from the R&D communities of III-nitrides, LEDs, lighting, displays, and optogenetics will overcome technological challenges and will ultimately enable the microLED technology to flourish to serve society at the broadest scale.

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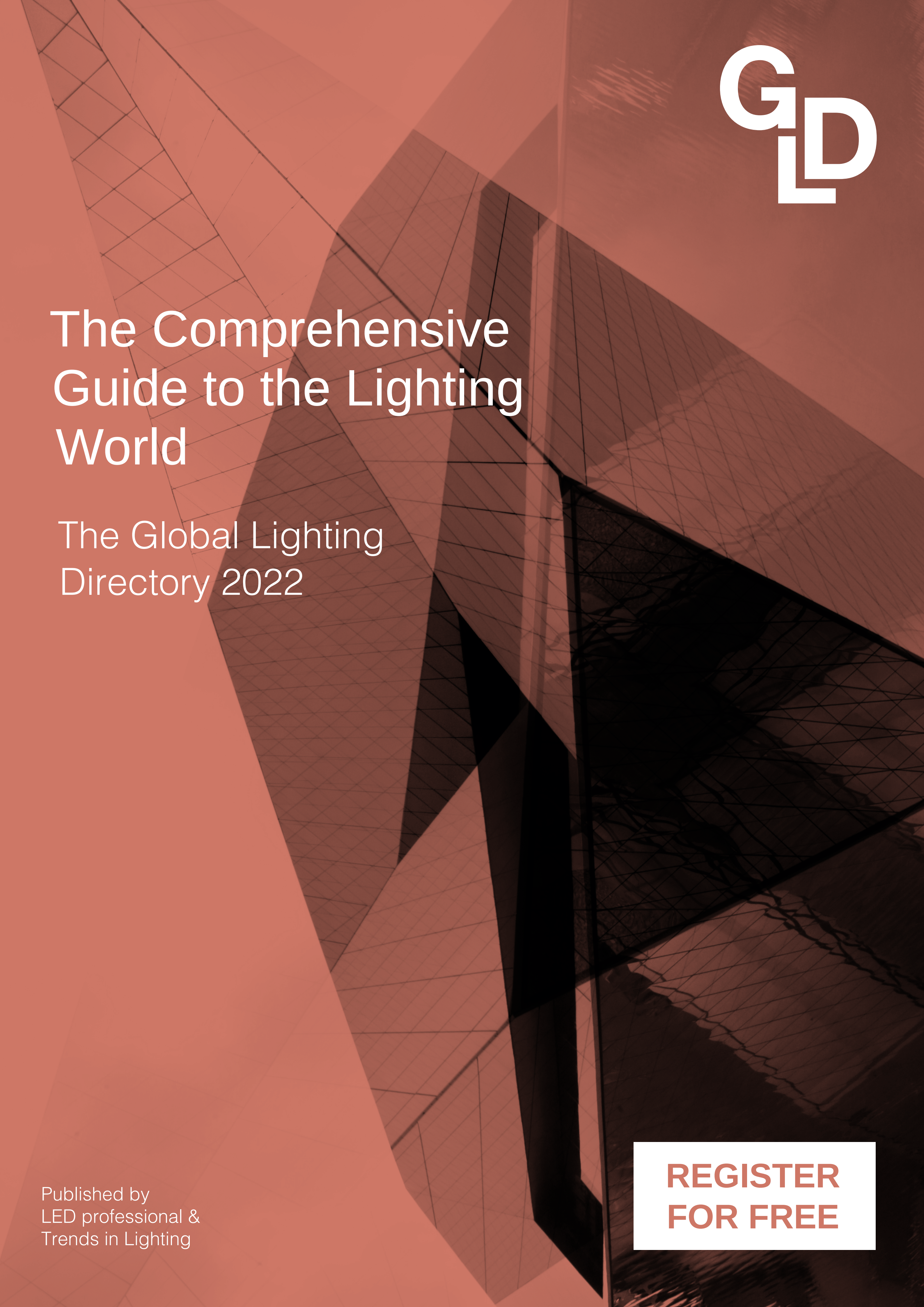
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Predictions of Melatonin Suppression During the Early Biological Night and Their Implications for Residential Light Exposures Prior to Sleeping

Mark S. REA[email], Rohan NAGARE & Mariana G. FIGUEIRO at Light and Health Research Center, USA

The magnitude of nocturnal melatonin suppression depends upon the spectrum, amount, and duration of light exposure. The functional relationship between melatonin suppression and the light spectrum and amount have been previously described. Only one duration-dependent parameter was needed to extend this functional relationship to predict nocturnal melatonin suppression during the early biological night from a variety of published studies. Those predictions suggest that ambient lighting commonly found in North American homes will not suppress melatonin for durations up to 3 h, whereas extended use of self-luminous displays in the home prior to sleep can.

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The circadian system is perhaps one of the most important non-visual systems affected by retinal light exposure. The retinohypothalamic tract (RHT) is the direct neural pathway from the retina to the master biological clock, the suprachiasmatic nuclei (SCN) in the hypothalamus. It is now known that the spectral, temporal, spatial, and absolute sensitivity characteristics of the RHT neural channel stimulating the SCN are quite different from those exhibited by the optic nerve leading to visual functioning by the thalamus and visual cortex. This is true even though all retinal photoreceptors, including the intrinsically photosensitive retinal ganglion cells (ipRGCs), participate in the various phototransduction processes for visual and non-visual systems [1–6]. To quantify light as a stimulus for the circadian system, it is necessary to develop a functional relationship between optical radiation incident on the retina and the spectral, temporal, and absolute responses of the SCN. Toward that end, classic psychophysical methods can be used [7].

Defining Light: The Photopic Luminous Efficiency Function, V(λ)

Psychophysics is a technique used to derive functional relationships between physical (Φ) stimuli and psychological (Ψ) responses (**Figure** 1). Like physical quantities, these psychological responses are always in the form of measurable behavioral responses, such as reaction times, subjective judgments, or nocturnal melatonin suppression.

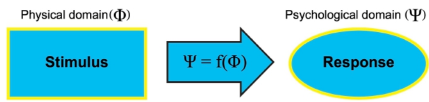

Figure 1: Psychophysics, first defined by Gustav Fechner in his treatise Elements of Psychophysics in 1860 [7], is the establishment of functional relationships between the physical domain (Φ), the measured stimuli, and the psychological domain (Ψ), the measured behavioral responses.

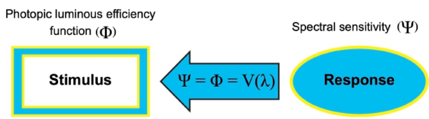

Figure 2: Once a psychophysical relationship has been established between the stimulus and the response, the behavioral response from the psychological domain (Ψ) becomes a measure of the stimulus in the physical domain (Φ). Early studies of the spectral sensitivity of humans to optical radiation became the foundation for the photopic luminous efficiency function, V(λ), which is now used to characterize light as a stimulus for human vision.

Radiometry is the physical measurement of optical radiation. A wide variety of behavioral responses can be measured for the very same optical radiation incident on the retina in psychophysical experiments. For example, exposure to a monochromatic wavelenght can evoke a reaction time, a subjective report of apparent brightness, a reported hue sensation, or suppression of melatonin synthesis. Each of those behavioral responses will have a different functional relationship to monochromatic wavelength exposure.

The goal of one set of psychophysical experiments conducted in the early part of the twentieth century was to define light as a physical quantity for the emerging lighting industry by establishing a functional relationship between the radiant power of monochromatic wavelengths to the relative sensitivity of the human visual system to those wavelengths. Since sensitivity cannot easily be measured directly, the basic rationale for these experiments was to measure psychological judgements of equality for two monochromatic wavelengths and then piece together a relative sensitivity function from all wavelengths that had been judged as equal. Specifically, if any two monochromatic wavelengths were reported to be equal, it was assumed that both would have been stimulated by the same physical amount of light.

Two equality techniques were used. One was based upon direct comparisons of the perceived brightness of two wavelengths while the other was based upon the disappearance of flicker for two rapidly oscillating wavelengths. For both techniques the radiant power of a reference wavelength was fixed and visually compared to a test wavelength with variable radiant power. The radiant power of the test was varied until the two wavelengths were judged equal (i.e., equal apparent brightness or no apparent flicker). The relative amount of radiant power needed by the test wavelength to be perceived as equal to the radiant power of the reference wavelength was then measured. Both of these equality methods were applied for pairs of wavelengths across the spectrum. From these psychophysically determined equal wavelengths, the wavelength requiring the least amount of radiant power to be equal to the others was at 555 nm. This was the wavelength to which people were most sensitive and therefore the peak of the spectral sensitivity function that would define light for the Commission Internationale de l'Éclairage (CIE). Once the CIE adopted this, so-called photopic luminous efficiency function, V(λ), in 1924 to define light, a system of measuring optical radiation as a visual stimulus was possible. Thus, through psychophysics one aspect of the psychological domain (*Ψ*), a spectral sensitivity function, became a member of the physical (*Φ*) domain, the photopic luminous efficiency function (**Figure 2**).

This 1924 system of photometry has been an extremely useful simplification for the lighting industry because the spectral characteristics of the (implicit) visual stimulus can be described in terms of a single quantity (e.g., luminance) without consideration of the spectral power distribution of the light source. Thus, intensity distributions (luminous intensity) and recommended light levels (illuminance) can all be defined in terms of a system of photometry based upon V(λ). Indeed, for many visual tasks that are processed by the fovea, like reading or on-axis detection, V(λ) is an excellent rectifying measure of the spectral characteristics of the visual stimulus [8]. In graphical terms, the psychophysically determined functional relationship can be shown as a plot of the physical quantity represented on the abscissa, in appropriate units (e.g., wavelength in nm), and the psychological response on the ordinate (e.g., reciprocal of the radiant watts seen as equal). For other behavioral responses like subjective brightness, however, V(λ) is not a suitable rectifying measure of the spectral characteristics of the visual stimulus (**Figure 3**) [9]. Short wavelengths, discounted by V(λ), strongly affect brightness response.

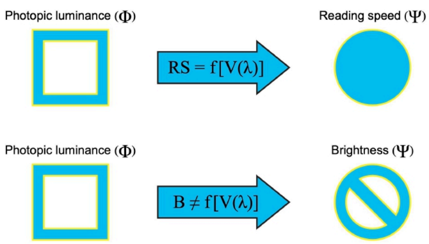

Figure 3: The photopic luminous efficiency function, V(λ), is excellent at characterizing the visual stimulus for reading materials, but not for subjective brightness. Therefore, light stimuli defined in terms of V(λ) in the physical domain (*Φ*) have only limited ability for establishing psychophysical relationships to other responses in the psychological domain (*Ψ*). B, brightness; RS, reading speed.

It should be noted that specification of the spectral characteristics of the visual stimulus does not represent a full specification of the stimulus. Additional psychophysical experiments need to be performed to establish a functional relationship between a set of physically measured stimuli and a psychological response. For example, to predict on-axis detection, the solid angle of the visual target and its contrast as well as the absolute luminance of the target background must be known. All of these stimulus characteristics provide input into the relative visual performance (RVP) model, which has been validated for reading speed and for a variety of other on-axis responses [10–14]. Once the functional relationship between the physical stimulus and psychological response is established, however, the response metric (e.g., RVP) becomes part of the physical domain (*Φ*) even if the physical stimulus is complex.

Defining Circadian Light and Circadian Stimulus

Given that the conventional measures of light based upon the photopic luminous efficiency function, V(λ), do not appropriately represent the circadian system's response to different wavelengths, a new spectral sensitivity function was needed. Circadian light (CL_A) was derived, in part, from binocular experiments [15,16] using monochromatic-light-induced nocturnal melatonin suppression as the outcome measure [17,18]. The pineal gland synthesizes melatonin at night and because there is only one major light-sensitive pathway from the SCN to the pineal gland [19,20], nocturnal melatonin suppression is an ideal way to measure the otherwise unreachable response of the human SCN to different spectra and amounts of retinal light exposure.

Circadian light (CL_A) was developed to be analogous to V(λ) but, as the name implies, to define light for the circadian system. Like V(λ), CL_A was based upon a particular type of psychophysical experiment, specifically, light-dependent attenuation of melatonin synthesis by the pineal gland at night. Using a constant criterion methodology to establish equality of response, it was possible to quantify the relative radiant power needed to suppress nocturnal melatonin synthesis by monochromatic light sources [15,16]. Although these data provided an important starting point for the development of CL_A, subsequent experiments with polychromatic sources showed that the response of the circadian system to broad-band spectra could not be predicted from the spectral sensitivity data obtained from monochromatic sources [21–23]. Specifically, under some conditions adding more light reduced the circadian system response; this is known as subadditivity. Consequently, a more complicated formulation of circadian light had to be developed to describe the spectral sensitivity of the circadian system to any spectral power distribution, monochromatic or polychromatic. This more complete formulation then, just like V(λ), moves CL_A from the psychological domain (*Ψ*) to the physical domain (*Φ*).

As already discussed, defining circadian light is not a full specification of the stimulus for the circadian system. A more complete specification would also include the operating range of the circadian system from threshold to saturation in addition to its spectral sensitivity. The metric circadian stimulus (*CS*) was developed for this purpose. As with CL_A, psychophysical experiments using nocturnal melatonin suppression informed the development of *CS*. The absolute sensitivity of the circadian system to luminous stimuli, quantified in terms of CL_A, was functionally described by *CS* for a 1-h exposure duration [24]. Thus, *CS* moved from the psychological domain (Ψ) to the physical domain (Φ) for specifying luminous stimuli for the circadian system.

CS is not a complete specification of the luminous stimulus, however. The duration of exposure is also important for describing the circadian system's response to optical radiation on the retina. The purpose of the present paper was to determine how the duration of exposure could be added to the CL_A and *CS* formulations to predict nocturnal melatonin suppression during the early biological night. Specifically, melatonin suppression data for different binocular exposure durations reported by Nagare et al. [25] were used to develop a more complete specification of the circadian stimulus.

Methods

Current *CS* Model

According to the circadian phototransduction model (**Equation (1)** and **Equation (2)**) proposed by Rea et al. [17,18,24], CL_A represents the spectral sensitivity of the SCN to light and *CS* represents its absolute sensitivity. Although the CL_A and *CS* formulations were based upon nocturnal melatonin suppression following a 1-h light exposure, the model is intended to represent the circadian system's instantaneous response to light exposures. To accurately predict the amount of nocturnal melatonin suppression for light exposures other than 1 h, however, the duration of light exposure must also be known.

$$CL_A = 1548 \int Mc_\lambda E_\lambda d\lambda + a_{b-y}\left(\int \frac{S_\lambda}{mp_\lambda}E_\lambda d\lambda - k\int \frac{V_\lambda}{mp_\lambda}E_\lambda d\lambda\right) - a_{rod}\left(1 - e^{\frac{-\int V'_\lambda E_\lambda d\lambda}{RodSat}}\right), \quad b-y>0$$

$$CL_A = 1548 \int Mc_\lambda E_\lambda d\lambda, \quad b-y \le 0 \quad (1)$$

where,

$$b-y = \int \frac{S_\lambda}{mp_\lambda}E_\lambda d\lambda - 0.2616\int \frac{V_\lambda}{mp_\lambda}E_\lambda d\lambda$$

CL_A: Circadian light, E_λ: light source spectral irradiance, *CS*: Circadian stimulus, Mc_λ: melanopsin sensitivity (corrected for crystalline lens transmittance), $k = 0.2616$, S_λ: S-cone fundamental, $a_{b-y} = 0.7$, mp_λ: macular pigment transmittance, $a_{rod} = 3.3$, V_λ: photopic luminous efficiency function, $RodSat = 6.5\,\mathrm{W\,m^{-2}}$, V'_λ: scotopic luminous efficiency function.

$$CS = 0.7 - \frac{0.7}{1 + \left(\frac{CL_A}{355.7}\right)^{1.1026}} \quad (2)$$

Test Dataset

The data published by Nagare et al. [25] (**Table 1**) were used to determine whether the *CS* formulation could be supplemented with an exposure duration term to predict nocturnal melatonin suppression in the early biological night. Nagare and colleagues measured light-induced nocturnal melatonin suppression in healthy adults and adolescents following binocular exposure to a wide range of light levels (40–1000 lx), two white-light spectra (2700 K and 6500 K), and extended nighttime light exposure durations (0.5–3.0 h). (The α-opic irradiances ($\mu\mathrm{W\,cm^{-2}}$) for the lighting interventions, following the SI-compliant approach recommended by the CIE [26] are provided in the original manuscript.) Statistical analysis showed that the main effect of participant age was not significant, nor were the two-way interactions between age and light level, spectrum or duration ($p > 0.05$), so the melatonin suppression values for the two age groups were averaged together for each combination of the four light levels, two spectra, and six durations.

Based upon the specific experimental setup as described in Nagare et al. [25], each study participant either operated an electronic device (e.g., filtered laptop or smartphone) or read a physical book on the desk. Retinal light exposures for each participant were monitored using a Daysimeter (Model 12, Lighting Research Center, Troy, NY) mounted on a lensless eyeglasses frame throughout the 3-h light exposure. A simple exercise was conducted wherein photometric measurements were taken to address any systematic offset in effective corneal stimulus due to misalignment between the participant line of sight and the orientation of the Daysimeter sensor. The exercise revealed that the effective light level at the participants' eye was reduced by an average of 23.4% (SD 2.5) and 16.8% (SD 3.2) while operating a smart phone or a laptop, respectively, and reduced by 24.3% (SD 3.7) when reading a book. Therefore, the CL_A values in **Table 1** were multiplied by a factor of 0.797 (aggregate), consequently reducing the effective *CS* levels for modeling purposes. Post hoc statistical analysis showed that the measured nocturnal melatonin suppression from Nagare et al. [25] and effective *CS* did not differ significantly ($p > 0.05$).

Mathematical Modeling

The statistical analyses reported in the original publication revealed that there was no significant interaction between light spectrum and duration ($p > 0.05$), suggesting that over the range of conditions employed by Nagare et al. [25] the spectral sensitivity of the circadian system did not change. It should be true then that the form of the sigmoidal four-parameter logistic function in **Equation (2)** would remain unchanged and the basic function simply would be shifted along the log CL_A abscissa as a function of exposure duration. Guided by parsimony and the assumption that spectral sensitivity did not change over 3 h, it was assumed for modeling purposes that only the half-saturation constant in **Equation (2)** (i.e., $CL_A = 355.7$) would systematically change as a function of exposure duration. Thus, **Equation (2)** was modified slightly (**Equation (3)**), whereby *q* was the only variable.

$$CS = 0.7\left[1 - \frac{1}{1+\left(\frac{CL_A}{q}\right)^{1.1026}}\right] \quad (3)$$

Spectrum	Amount		Nocturnal melatonin suppression (%) by exposure duration (h)					
	CS	CL_A	0.5 h	1.0 h	1.5 h	2.0 h	2.5 h	3.0 h
2,700 K	0.06	41.6	− 1	2	2	2	3	6
	0.11	77.5	2	7	7	5	11	13
	0.27	233.2	12	17	21	22	25	25
	0.45	606.2	26	39	45	50	53	58
6,500 K	0.06	41.6	2	5	0	− 1	5	8
	0.11	77.5	3	7	11	12	17	19
	0.28	246.3	19	28	33	37	40	44
	0.46	641.7	26	43	51	57	61	65

Table 1: Nocturnal melatonin suppression, in percent, from Nagare et al. [25] together with the average *CS* and CL_A levels recorded by participants' Daysimeters, light-weight, head-mounted devices developed by Bierman et al. [27] to measure individual light exposures during the experiment.

Results

Test Dataset Optimization

Best fitting logistic functions based upon **Equation (3)** and developed using curve fitting software OriginPro 2020 (OriginLab Corporation, Northampton, MA) for the six different exposure durations from Nagare et al. [25] are shown in **Figure 4**. All the curves fit the melatonin suppression data significantly ($p < 0.001$) and the goodness of fit as assessed by the coefficient of determination (R^2) was always greater than 0.90. The optimized half-saturation constant (q) values ranged from $CL_A = 168.3$ for the 3.0-h test dataset to $CL_A = 758.0$ for the 0.5-h test dataset.

The free parameter, q, in **Equation (3)** can be considered as a light exposure (amount × duration) term, where

$$q = q_m\, t^r \qquad (4)$$

and t is the duration of light exposure, in hours, q_m is the amount of measured light, in terms of CL_A, producing half saturation and, to avoid any assumption of reciprocity between the amount of exposure and the duration of exposure, r is a free parameter. In the original model by Rea and colleagues, $q = 355.7$ for a 1-h exposure duration. Subsequent modeling combining **Equation (3)** and **Equation (4)** resulted in optimized values of $q_m = 411.3$ and $r = -0.855$ (**Equation (5)**). The left panel in **Figure 5** shows the functional relationship between exposure duration (in hours) and the optimized half-saturation values, q, from **Figure 4**.

$$CS_t = 0.7\left[1 - \frac{1}{1+\left(\frac{CL_A}{411.3\ t^{-0.855}}\right)^{1.1026}}\right] \qquad (5)$$

where, CS_t corresponds to the absolute response of the SCN as characterized by nocturnal melatonin suppression following a light exposure duration of t in hours.

The goal of the present study was to investigate whether the CS function can be simply supplemented by adding light exposure duration (t) as an independent stimulus parameter. Since there was no significant difference between the CS formulation based upon a 1-h exposure and the 1-h suppression data from Nagare, et al. [25] (**Table 1**), the optimized function (CS_t, **Equation (5)**) was simplified. In the original CS model (i.e., based on 1-h exposure), $q = 355.7$, so in the simplified **Equation (6)**, q_m becomes a constant, $q_m = 355.7$, and to obviate the exponent, r, entirely $r = -1.0$. Thus,

$$CS_t = 0.7\left[1 - \frac{1}{1+\left(\frac{CL_A}{355.7\ t^{-1}}\right)^{1.1026}}\right] \qquad (6)$$

Figure 5 illustrates the optimized half-saturation function, where $q_m = 411.3$ and $r = -0.855$, and the simplified half-saturation function, where $q_m = 355.7$ and $r = -1.000$. In the simplified CS_t function (**Equation (6)**), CL_A and t are the only unknowns. Absolute predictions based upon the proposed CS_t function (**Equation (6)**) are depicted in **Figure 6** for the six durations, from $t = 0.5$ h to $t = 3.0$ h.

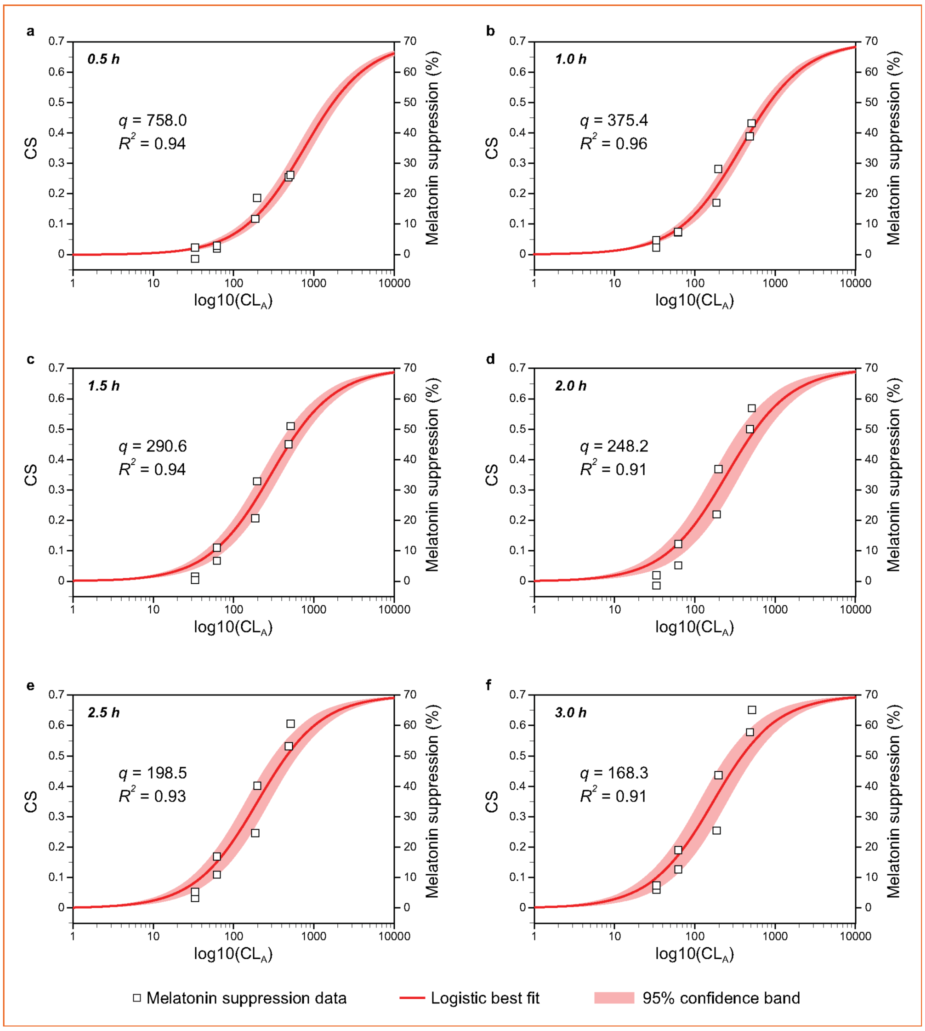

Figure 4: Optimized logistic functions from Equation 3 relating nocturnal melatonin suppression to log CL_A for different exposure durations (0.5–3 h [**a–f**, respectively]) together with a summary of the inferential statistics. The only free parameter was q, the half-saturation value for each exposure duration.

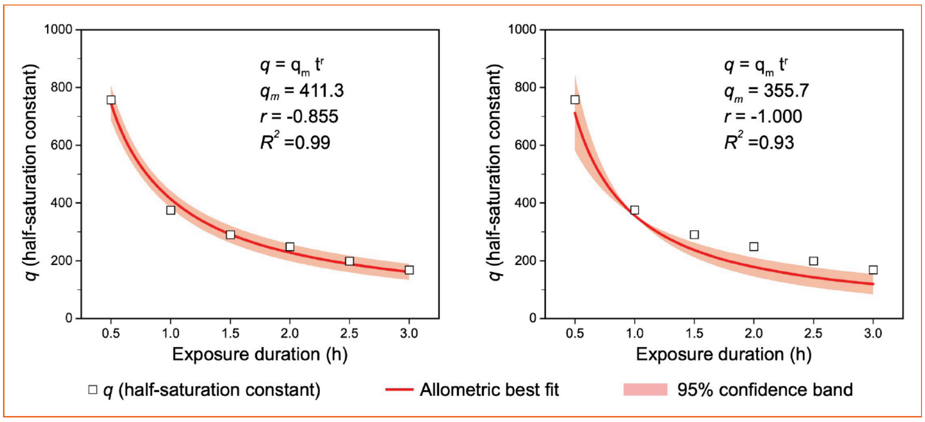

Figure 5: Optimized half-saturation function (**left**) where $q_m = 411.3$ and $r = -0.855$, as well as a simpler half-saturation function (**right**), consistent with the original model by Rea et al. [17], where $qm = 355.7$ and $r = -1.000$; q_m is the same as the original model and r was simply obviated.

Validation

To validate the simplified function, it was possible to compare the predicted CS_t values with nocturnal melatonin suppression data from 11 published studies [28–38]. **Figure 7** shows the calculated melatonin suppression data from the selected studies along with a priori predictions from the simplified function (**Equation (6)**; **Figure 6**).

All the curves fit the melatonin suppression data significantly ($p < 0.001$). Except for the 2.5-h exposure duration, the goodness of fits, R^2, were greater than 0.80. For the 2.5-h dataset, there simply were not enough data to produce statistically reliable curve fits. Nevertheless, the CS_t predictions for 2.5 h go through the center of the melatonin suppression data and, in addition, the fits for the flanking 2.0-h and 3.0-h data were well predicted by the simplified function. These two pieces of indirect supporting evidence suggest that the simplified function is reliable for predicting nocturnal melatonin for the 2.5-h duration.

Figure 8 shows the relationship between CS_t (now in the physical domain, Φ) and melatonin suppression for the data used in the validation exercise. Taken together, the validation exercise using independent data supports the utility of the sumplified function, CS_t, for predicting melatonin suppression during the early biological night.

Discussion

In the present study we showed that the original *CS* formulation proposed by Rea et al. [17,18,24] could be used to predict the amount of nocturnal melatonin suppression during the early biological night for different durations of exposure by adding just one additional duration-dependent parameter, *t*. These findings indirectly support the inference that CL_A and *CS* are robust specifications of the instantaneous luminous stimulus for the circadian system in terms of both spectrum and amount. To predict the amount of nocturnal melatonin suppression, however, CL_A and *CS* are only part of the stimulus specification. As is well known, and shown here, the duration of exposure must also be specified. The simplified CS_t formulation was not only useful for predicting the data from Nagare et al. [25] but provided excellent explanatory power for several other published studies. Thus, specification of the luminous stimulus for suppressing nocturnal melatonin during

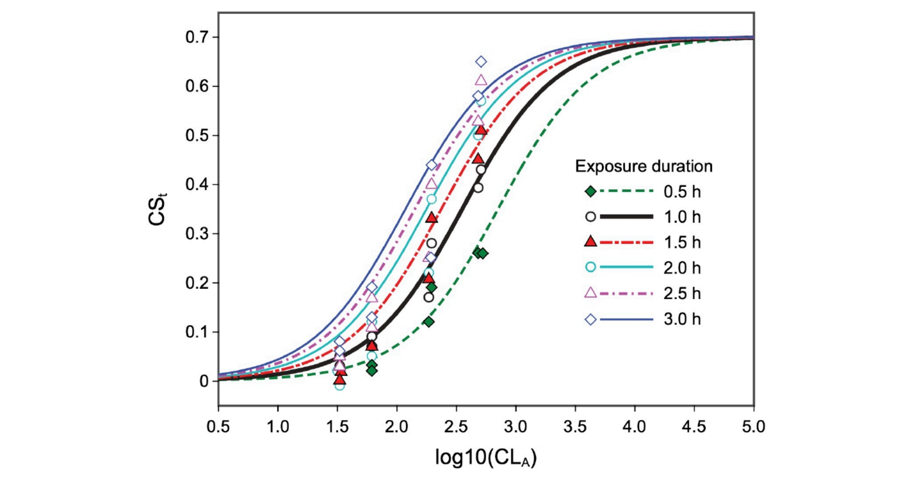

Figure 6: All the data from Nagare et al. [25] together with simplified CS_t functions for the six light exposure durations (t = 0.5 to 3.0). The solid black line represents the original *CS* function based upon 1-h exposure (t = 1.0). As can be readily appreciated, it is important to augment the *CS* formulation (Equation 6) to include a dynamic factor for duration of light exposure to predict absolute melatonin suppression.

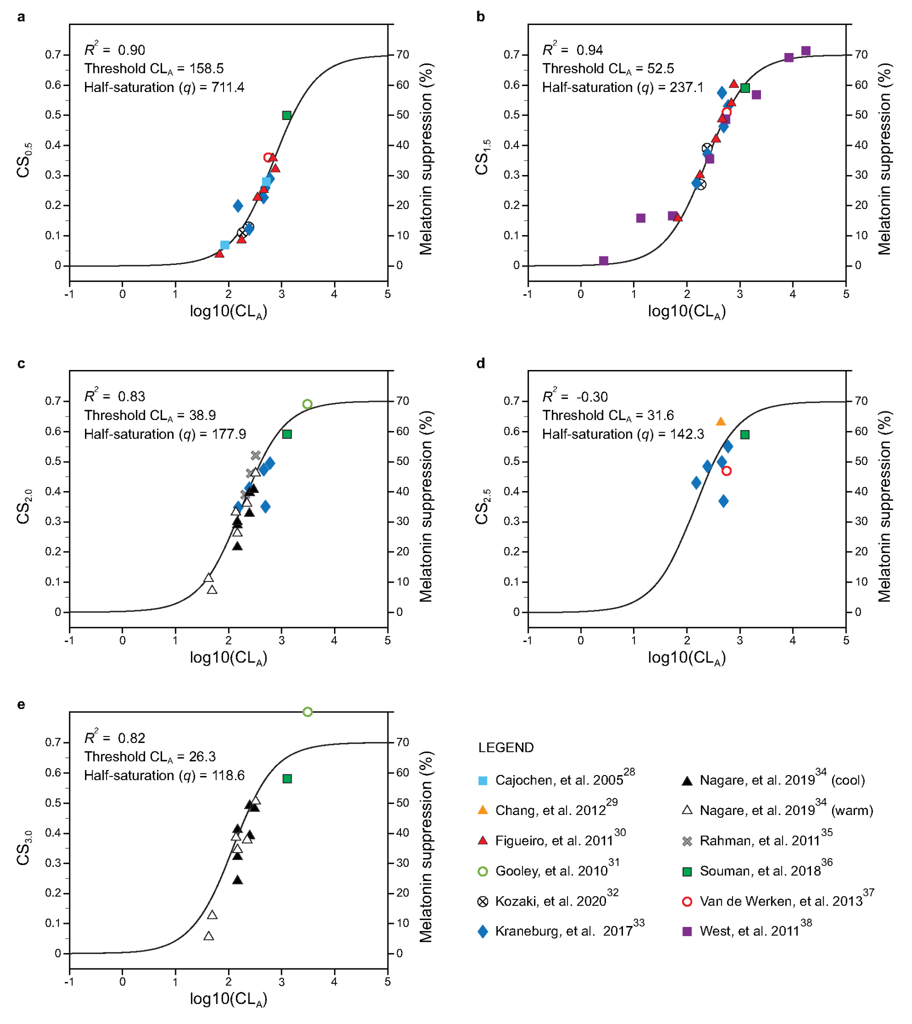

Figure 7: Simplified CS_t function predictions for measured or calculated melatonin suppression for exposure durations of 0.5 h (**a**), 1.5 h (**b**), 2.0 h (**c**), 2.5 h (**d**), and 3.0 h (**e**). Since the 1-h data were used to estimate *CS*, the data for this exposure duration could not be legitimately included in the validation exercise. Threshold CL_A corresponds to circadian light levels estimated to induce nocturnal melatonin suppression of 10%.

the early biological night can be described in terms of CS_t which itself is defined in terms of the spectrum (CL_A), the amount (CS), and the exposure duration (t) of the luminous stimulus.

The implications of the simplified function, CS_t, are perhaps most relevant to light exposures in residences prior to sleeping. It is important that evening light not disrupt the circadian system, both in terms of delaying circadian phase and attenuating melatonin synthesis. In that regard, it had been suggested by Rea and Figueiro [39] that most residential lighting would not produce sufficient light exposures (for typical spectra, amounts, and durations in residences) to significantly suppress melatonin synthesis. Specifically, Rea and Figueiro suggested, as a stated conservative threshold, that people at home in the evening should limit their light exposures to "white" light to 30 lx at the eyes for 30 min. The laboratory study by Nagare et al. [25] provided a more precise estimate of exposure threshold, suggesting that light exposures to white light in residences should be limited to 50 lx at the eye for 2 h. These suggested exposure limits rely, first, on an assumption about the threshold for light-induced nocturnal melatonin suppression (≈ 10%) and, second, on empirical measurements and observations of lighting in residences in North America and Europe.

A nocturnal melatonin suppression exposure threshold of 10% was chosen for two reasons. First, the 10% value appears to be a good indicator of the "toe" of the logistic function relating log CL_A to nocturnal melatonin suppression (e.g., **Figure 4**) and, second, because the uncertainty is approximately 10% in melatonin measurements using radioimmunoassay methods [39].

Several studies have reported the amount of light, usually in photopic illuminance (lx), that were or might be incident on the corneas of occupants in their residents. A study by Burgess and Eastman [40] reported a mean light exposure of 33.0 lx (SD 13.8) over 4 h prior to bedtime, as measured using pendant actiwatches. Scheuermaier et al. [41] reported a mean light exposure of 34.8 lx (SD 24.1) prior to bedtime (19:00–00:00) for healthy young and older adults, measured using wrist worn actiwatches. In an extensive study involving 72 female school teachers, Rea et al. [42] reported mean evening residential vertical light levels of 28 lx, recorded using headband-Daysimeters [27] between civil twilight and bedtime.

Warm incandescent, CFL, or LED sources of approximately 2700 K dominate the residential lighting market [43]. According to the simplified function, CS_t, a photopic illuminance of 34 lx from both the Burgess and Eastman and the Scheuermaier et al. studies from "warm" sources translates into $CS_{1.0}$ = 0.04 for a 1-h exposure and $CS_{3.0}$ = 0.10 for a 3-h exposure (**Figure 9**). A photopic illuminance of 28 lx from the Rea et al. study translates into $CS_{1.0}$ = 0.03 and $CS_{3.0}$ = 0.09.

In modern homes, however, it is probably common today for occupants to experience prolonged light exposures from self-luminous displays. For instance, Gringras et al. [44] reported that smartphones (iPhone 5S) operated from a typical reading distance (22.5 cm) can deliver a light level of 51 lx at the eye. For typical self-luminous spectra, this would translate into $CS_{1.0}$ = 0.12 and $CS_{3.0}$ = 0.29 (**Figure 9**). Chang et al. [45] recorded an average photopic light level of 32 lx at the eye (n = 12) from eReaders, which translates into $CS_{1.0}$ = 0.06 and $CS_{3.0}$ = 0.17 (**Figure 9**). In a more extensive study of self-luminous tablets following up on the earlier work by Wood et al. [46], Nagare et al. [47] reported that iPads deliver around 70 lx at the eye for an average viewing distance of 30.5 cm; this translates into $CS_{1.0}$ = 0.13 and $CS_{3.0}$ = 0.30. Using the "Night-shift" setting for the same tablets, $CS_{1.0}$ = 0.08 and $CS_{3.0}$ = 0.21, respectively. In general, **Figure 9** shows that evening ambient light exposures in res-

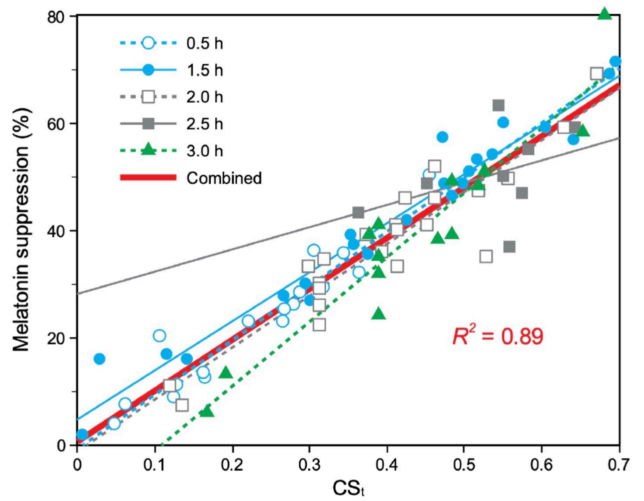

Figure 8: The relationship between the physical stimulus ( ), measured in terms of CS_t, and the measured melatonin suppression responses ( ) from the validation studies. The symbols correspond to melatonin suppression datasets at the various exposure durations. The lines for each exposure duration correspond to the best fitting linear trends across the respective datasets, whereas the continuous (solid red) line depicts the trend across the five datasets combined. Ignoring the data set for 2.5 h (see text for "Discussion" of this duration), the R^2 value was 0.91.

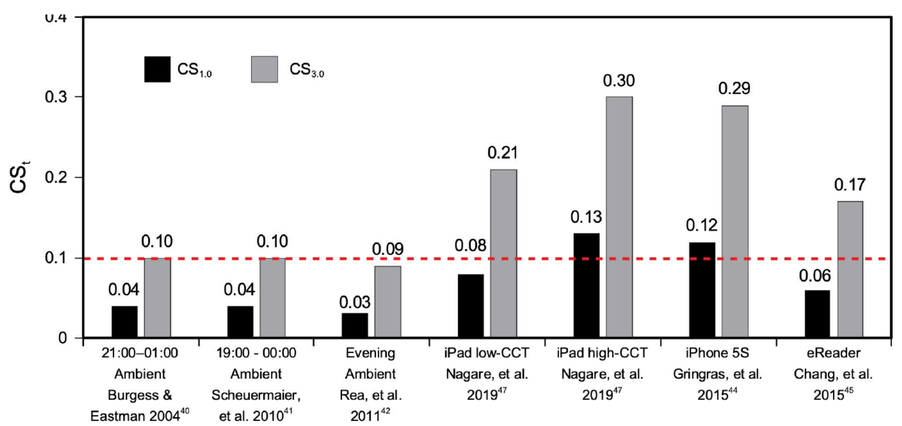

Figure 9: CS_t predictions prior to bedtime with typical ambient lighting in residences and with self-luminous devices for durations of 1 h and 3 h. The dashed red line depicts the proposed threshold for activation of the human circadian system.

idences are typically below the proposed threshold of CS_t = 0.10, even after 3 h. For self-luminous displays that might be used in the home, however, predicted CS_t levels are often well above the proposed threshold, even when using the "Night-shift" setting [47].

Cautions associated with the simplified CS_t function deserve mention. Although the present study supports the assumption that the spectral and absolute sensitivities of the SCN are well characterized by CL_A and CS, respectively, it should not be assumed that the duration term, t, is applicable to melatonin suppression at every time of night. The dataset from Nagare et al. [25] from which the simplified function was developed, were collected at clock times when control night melatonin levels were increasing. Thus, until further research is completed, the simplified function should only be applicable for predicting nocturnal melatonin suppression on the rising part of the melatonin curve. In this regard, Phillips et al. [48] have shown that prolonged exposures to light prior to predicted DLMO attenuate the impact of light-induced melatonin suppression at night and, moreover, their particular protocol adds significant variance among subjects to the threshold for melatonin suppression. Perhaps a more obvious caution, the duration term in the simplified function should not be used to predict light-induced phase shifts, during the night or during the day. Even though CS_t may be a good representation of the light stimulus to the SCN, light-induced phase shifting responses may not have the same functional relationship to the light stimulus as light-induced nocturnal melatonin suppression. For example, studies have shown that light-induced nocturnal melatonin suppression is different than light-induced phase response [49,50]. Therefore, more research is needed to model the potentially interactive phase response characteristics of the SCN to combinations of spectrum, amount, and duration.

Conclusions

The present study extended the Rea et al. model by introducing a duration-dependent parameter and a proposed simplified formulation, CS_t, to predict nocturnal melatonin suppression during the early biological night. Data from a variety of published studies supported quantitative CS_t model predictions of nocturnal melatonin suppression. Overall the simplified CS_t formulation should be helpful in setting guidelines to limit melatonin suppression for residential applications where people are exposed to light prior to sleeping. ■

Data availability

The data supporting this study's findings are available from the corresponding author upon reasonable request. This manuscript was first published in Scientific Reports (2020) 10:14114 https://doi.org/10.1038/s41598-020-70619-5. Supplemental materials are included therein.

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Metamerism and Spectral Power Distribution Adjustment, the New Paradigm of LED Technology to Improve the Lighting Applications

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Since the appearance of LEDs on the market, thanks to their capabilities, this technology has revolutionized the lighting business in every way. Initially, applications were focused on improving the efficiency for visual tasks only, but now, proper lighting designs and applications must consider all the possibilities that offer this technology. The spectral power distribution customization is an important one, because thanks to the possibility of its precise adjustment in combination with the metamerism phenomenon, we can offer users solutions with the same color perception, but with enhanced features that are critical for a specific application.

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Introduction

In recent years, thanks to the spectacular development of LED technology, the lighting field has evolved rapidly to be able to implement this technology and get the maximum benefit and performance out of it. As we all know, nowadays, among the many advantages that LEDs provide us with, we could highlight their greater efficiency, better light control, the possibility of instant dimming and their high chromatic performance. But maybe the most relevant thing is that for the first time, lighting engineers have a source of artificial light that we can adapt spectrally precisely according to the needs of the environment, as well as the different applications. Thus, for the artificial lighting of spaces occupied by humans, especially those with limited access to natural light, we cannot just limit ourselves to ensuring minimum normative levels of illuminance in workspaces, we must also be able to provide a solution to their real needs, and find an optimal balance between the different types of vision (**Figure 1**):

- Image formation – Vision related to the photoreceptors, whose main purpose is to satisfy visual needs in order to perform assigned tasks and to perceive the environment correctly.
- Non-image formation – Sensitivity related to photoreceptors, the purpose of which is different from visual needs, such as synchronizing people's circadian rhythms with the solar cycle or controlling pupil contraction, among other functions.

The balance between the different types of vision is crucial to ensure the proper efficiency of our facilities and the well-being of users, as well as the labor productivity of workers depending on the tasks they have to perform in these environments.

To achieve an optimal balance between these different aspects, some of them antagonistic, a great tool available to engineers is the metamerism phenomenon, whereby humans have the same color perception based on different spectral power distributions (SPD). Thus, thanks to this phenomenon, two light sources with different spectral distributions provide us with the same color perception, when they produce the same level of excitation or response in the cones, the photoreceptors responsible for color perception. In this example, we can see the spectral power distributions of an incandescent lamp versus a standard LED 3000 K, which show us a very different spectral power distribution, but weighted by the sensitivity curves of the cones, (Blue or Short, Green or Medium and Red or Large) generate almost the same level of response (**Figure 2**):

- White LED CCT 3000 K
- Incandescent Lamp

At this point, we can already intuit that the demand for a specific color perception or CCT in a given environment, does not imply that it is not possible to carry out a spectral optimization of the installation based on other factors that are equally or more important than the user's own perception of color. In this process, the LED technology plays a very important role and offers us different options, which can be segmented into two main types: the application based on compact LEDs, and those based on a combination of independent LEDs.

Compact LED or Package Solution

Compact solutions are those based on the use of LEDs spectrally adapted to the different needs of the users, which are encapsulated in a standard format by the LED manufacturer, allowing a quick implementation by the luminaire manufacturers, as well as easy control as no special controller is needed.

Obviously, this type of solution forces LED manufacturers to implement complex engineering and adjustment processes in their factories to ensure optimal spectral performance and stability during the lifetime of the product under normal working conditions.

Depending on the materials used and the manufacturing process, we currently have at our disposal various types of compact LEDs or packages in standard format, which offer specific spectral characteristics, allowing them to be adapted to different environments depending on the parameters that need to be optimized. Structurally analyzing these LEDs (**Figure 3**), we can see that, broadly speaking, they all share a similar structure for obtaining white light, but there are very significant technological differences depending on the conversion technology used and the type of emitting die implemented. In this article, we will analyze the most relevant types that can be found on the market today.

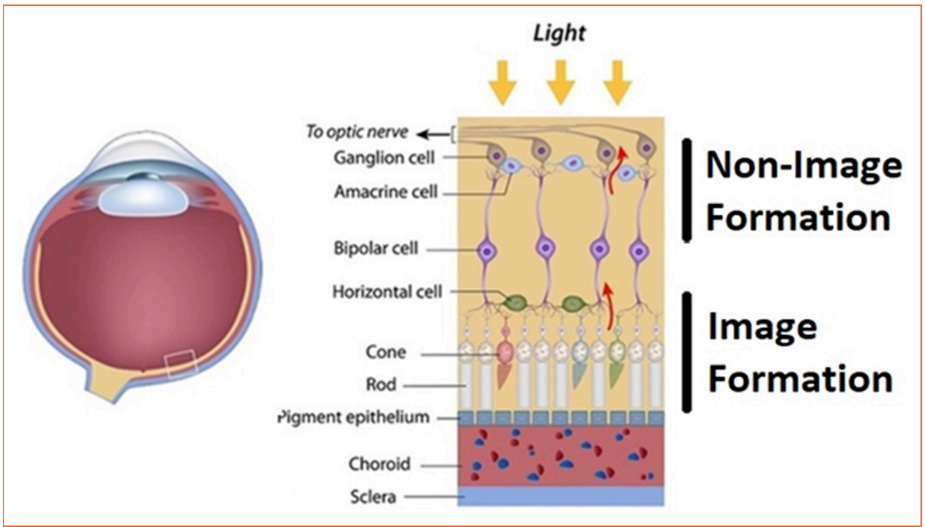

Figure 1: Retinal cress section.

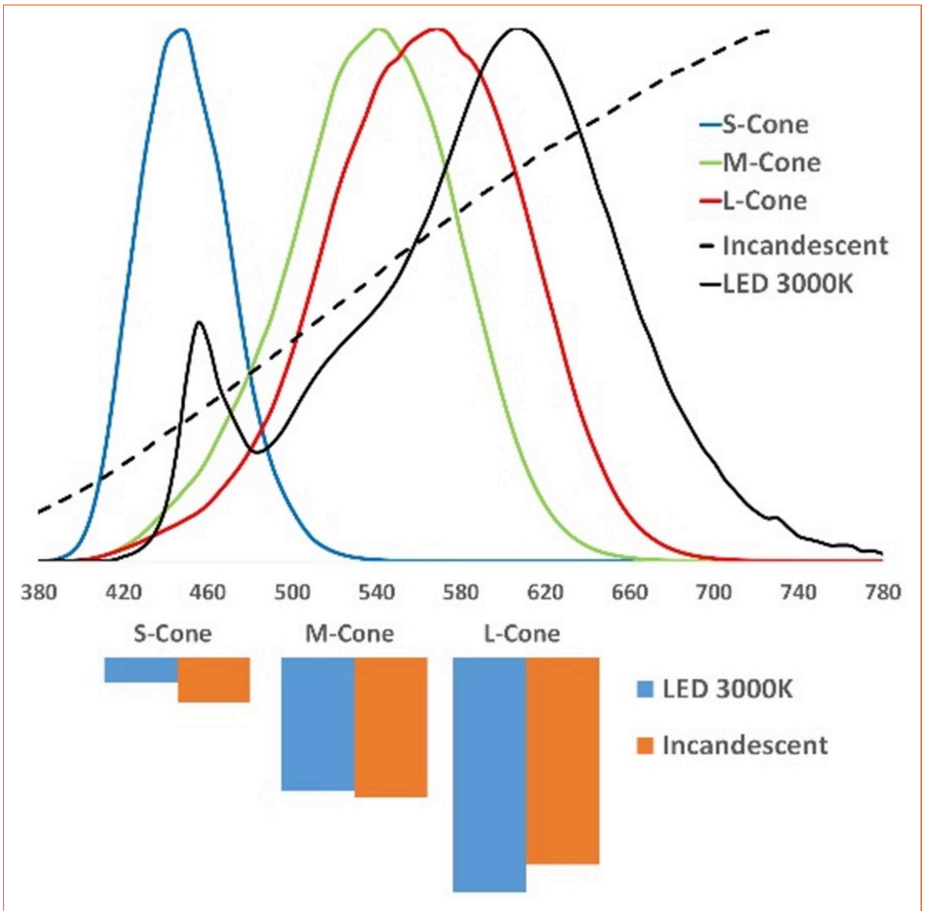

Figure 2: LED & Incandescent lamp SPD weighted for the different cones sensibility.

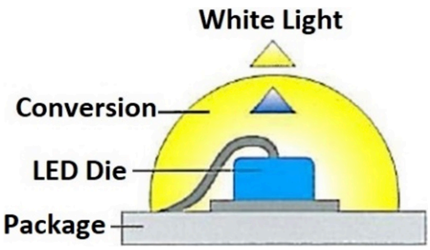

Figure 3: LED package section.

Compact LED with Blue-Based Pump Emission

Due to the level of market introduction, we can consider blue (λ 440–460 nm) pump emission LEDs with phosphor coating as the reference model, as this is currently the most widely used technology in the lighting market. The engineering of this type of LED is oriented towards maximizing lumen output and efficiency of the package, leaving other equally or more important features in second place. Its evolution has been mainly linked to the evolution of the conversion phosphors used to obtain highly efficient visible white light over the entire required color temperature range. In this aspect, one of the handicaps of this technology is the significant reduction in efficiency for high color rendering indexes CRI≥90. As we can see in (**Figure 4**), increasing the color rendering index from CRI 80 to CRI 90 implies an increase in red conversion phosphors, which, due to their wide conversion range, when weighted by the photopic viewing curve, generates a reduction in system efficiency.

Technological advances in phosphors and dosing processes in recent years have significantly reduced this efficiency differential between CRI 80 and CRI 90 LEDs, but it has been the introduction of Quantum Dots (QDs) mixed properly with the phosphors, which has allowed us to minimize or eliminate this differential thanks to its precise and narrow spectral conversion range. This allows us to optimize the spectrum of high CRI LEDs to ensure similar efficiencies to low CRI LEDs for the same CCT (**Figure 5**).

Despite this improvement, we can clearly see that this technology has some spectral weaknesses, especially the valley in the wavelength of maximum melanopic sensitivity, as well as the proximity of the blue emission peak to the peak of maximum probability of retinal damage (*Bλ*) according to the standard for photobiological safety UNE-EN 62471.

Compact LED with Cyan-Based Pump Emission

The Cyan (*λ* 460–470 nm) pump emission technology can be considered as an evolution of the Blue (*λ* 440–460 nm) pump emission, which provides some improvements from the spectral point of view. As we can see in **Figure 6**, this technology provides us with a reduction of the valley in the wavelength of maximum melanopic sensitivity, while it provides us with a greater safety margin with respect to the peak of maximum probability of retinal damage.

Thus, shifting the emission peak of the Cyan Pump technology, combined with a correct selection of the conversion phosphors, provides a significant increase in melanopic light (EML), while achieving a greater safety margin with respect to the probability of retinal damage (LB), shifting the emission from the violet to the turquoise band, negatively, we have a reduction in the system's efficiency (lm/W). In **Figure 7**, we can see the average values obtained in an application of CCT 5000 K – CRI 80 LEDs based on Blue Pump vs Cyan Pump emission technology.

Compact LED – Violet Die Emission

The Violet (*λ* 410–430 nm) pump emission technology is a more complex technology, as it requires the use of a wider range of RGB phosphors to convert violet emission into visible white light (**Figure 8**). The use of these wider types of phosphors allows to optimally adjust and adapt the light emission to natural light, offering color rendering indexes equal or close to CRI 100.

The main problem with this technology is the conversion losses in the phosphors together with the efficiency of the violet emission die, which generates a notable reduction in the efficiency (lm/W) of the system, as we can see in **Figure 9**, where we compare these technologies based on reference LEDs with the same color temperature CCT 5000 K.

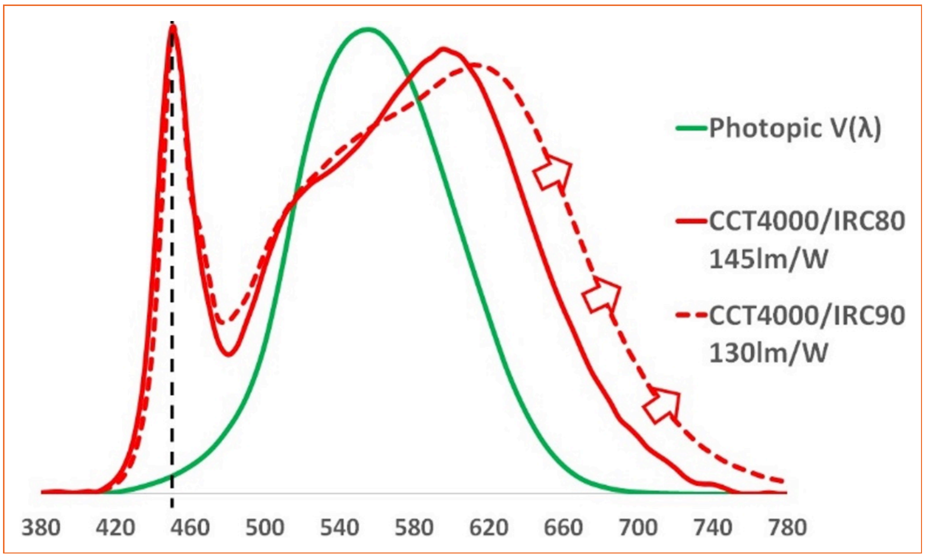

Figure 4: LEDs CCT 4000 K CRI 80 vs CRI 90 efficiency.

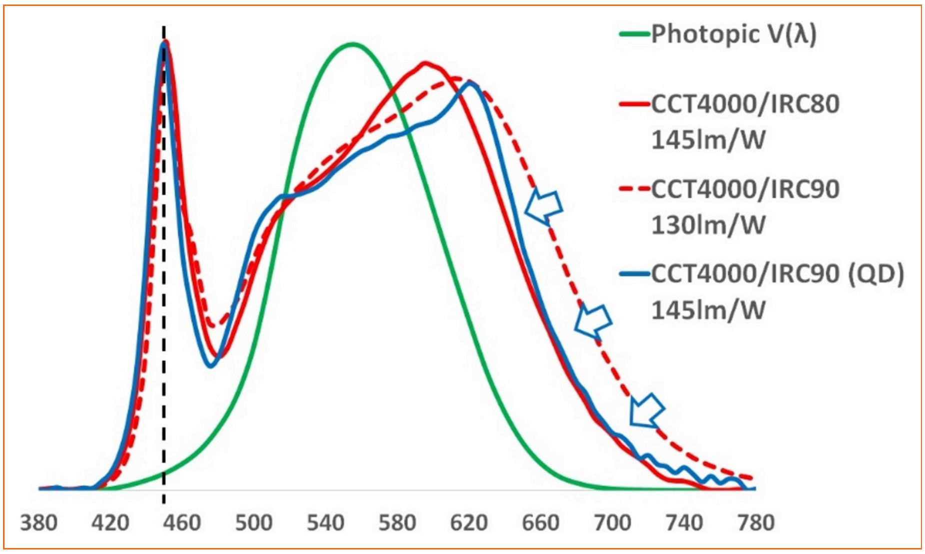

Figure 5: LEDs CCT 4000 K CRI 80 vs CRI 90 vs CRI 90QD efficiency.

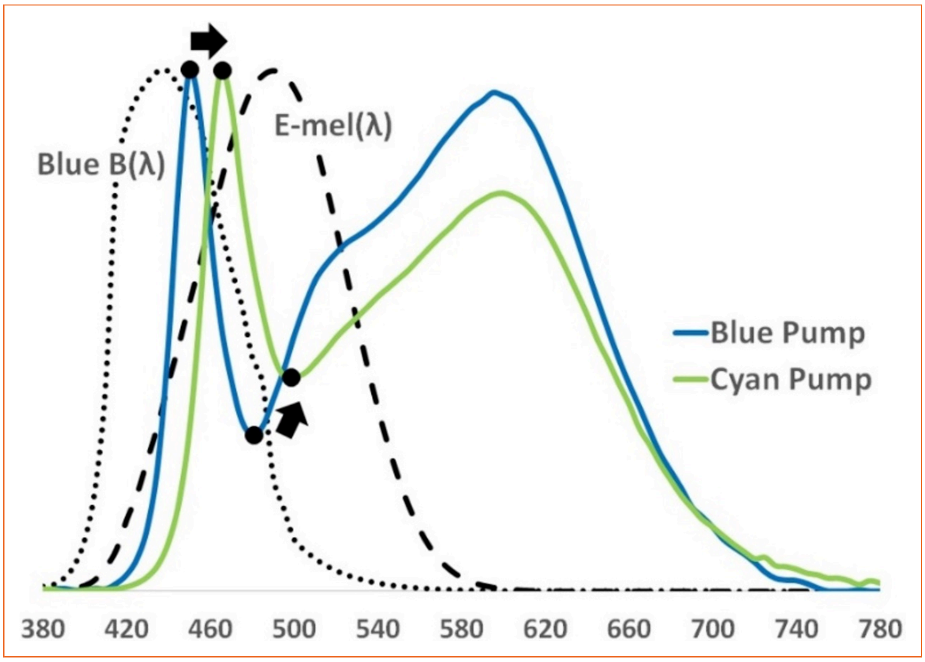

Figure 6: SPD LEDs based on Blue pump vs Cyan pump emission.

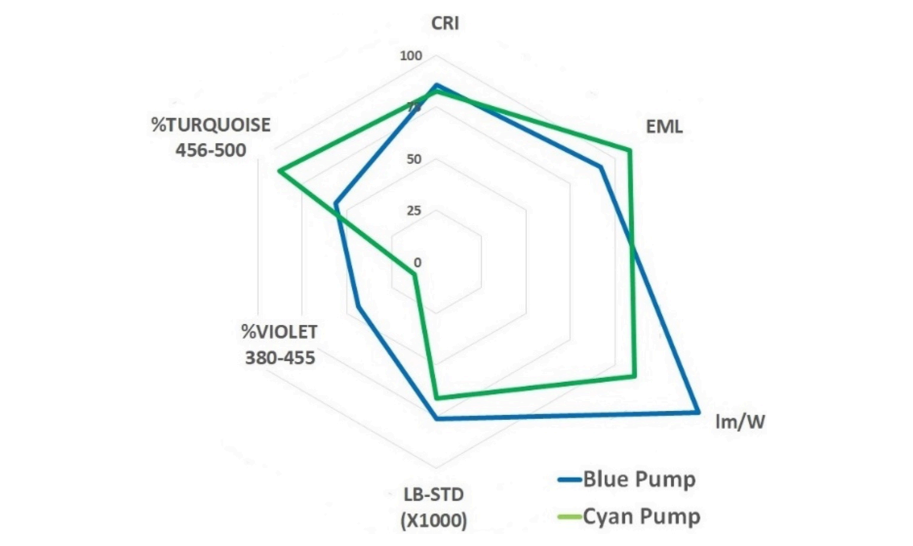

Figure 7: Reference values with LEDs implemented in a standard troffer 60 × 60 low glare in same test condition.

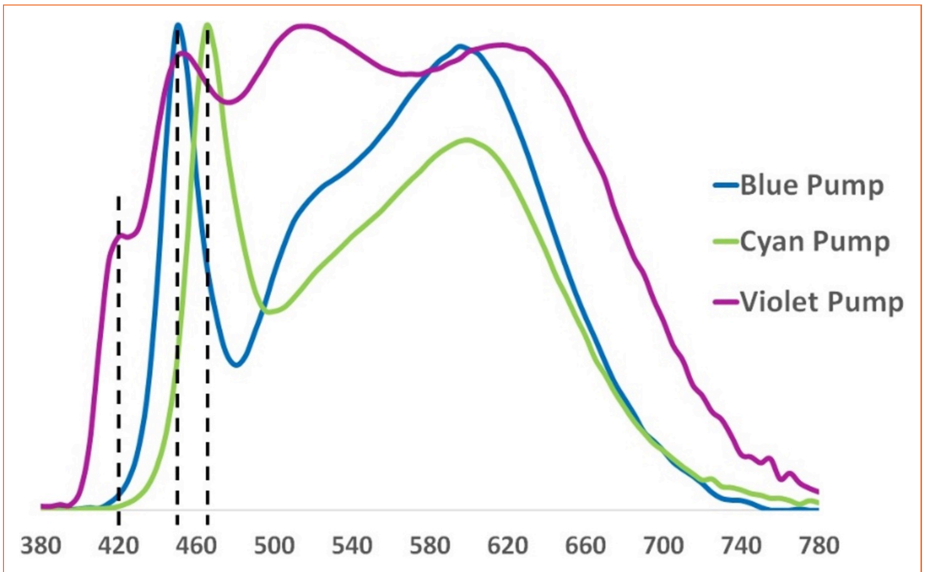

Figure 8: SPD LEDs based on Blue, Cyan, and Violet Pump.

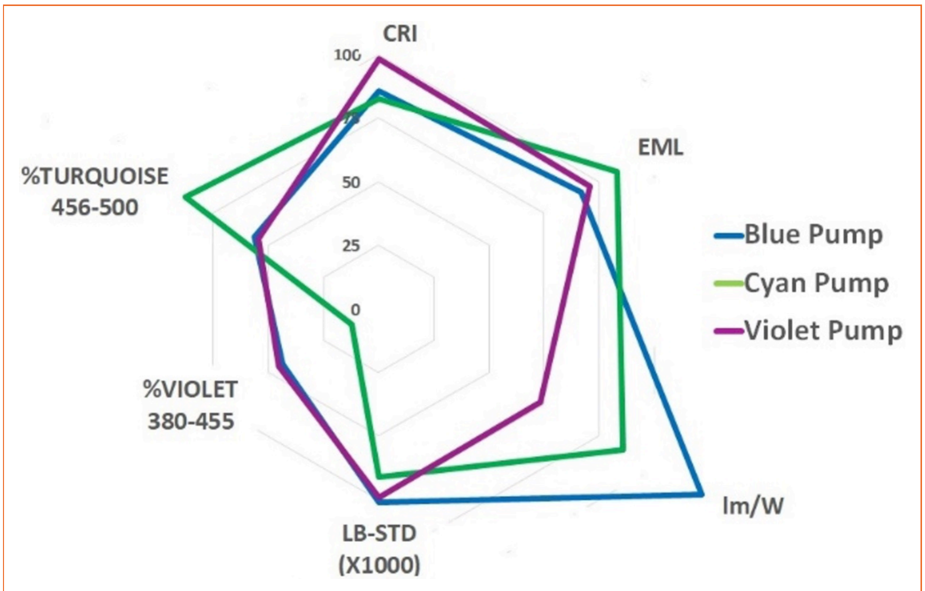

Figure 9: Reference values with LEDs implemented in a standard troffer 60 × 60 low glare in same test condition.

Compact LED – Multi Die Emission

This technology is an evolution of the previous ones, and is based on the implementation of more than one emitting die in the same compact package. In such applications, we can implement dies of the same type, in order to increase the lumen output or efficiency of the system, or on the contrary, we can implement dies of different types in order to have a wider rank of spectral modulation. As an example, in **Figure 10** we can see a commercial application of CCT 4000 K / CRI 80 LED with double die, Blue + Cyan pump emission, and phosphor conversion.

This configuration is more complex for LED manufacturers, as it involves greater technological challenges to ensure the stability of the system throughout its useful life, but on the other hand, it allows us to design compromise solutions between the technologies described in the previous points, so that depending on the type of dies implemented, as well as the combination of phosphors, we can adjust the system to achieve an optimum balance between the critical variables of each application or user needs for the same color perception or CCT. Thanks to the versatility offered by multi-chip technology, nowadays we can find different compact applications with very different spectral configurations that can be adjusted or adapted to the specific needs of each application on the market.

Array Independent LEDs

In parallel to the technologies we have seen in the previous points based on compact LEDs, we can also find options based on the use of different numbers and types of LEDs forming a matrix of light emitters on the market. In this type of application, the more different types of LEDs used, the more control and spectral adjustment possibilities we will have at our disposal, although obviously, the control systems required is more complex . In the **Figure 11** we can see an example of an application based on 4 independent LEDs that allow us a great rank of spectral modulation in the color space of cool and neutral white and saturate light.

This technology offers a high capacity for customization and adaptation, allowing a multitude of combinations with very precise spectral adjustments, but obviously, they are complex systems, which require advanced optical groups to ensure uniformity of the LED array emissions and must avoid chromatic aberrations, as well as complex control systems to ensure the stability of the system in normal operation during the product's life.

Conclusions

Nowadays, thanks to the spectral adjustment technologies available, together with the in-depth knowledge of the effects of the light spectrum on people, we can no longer limit ourselves to offering basic solutions aimed solely at general lighting and energy efficiency, to the market. On the contrary, it is the duty of technicians to analyze the environment and the needs of users in order to find solutions to their problems, even those they are still unaware of or accept with resignation. Thus, we must optimize the systems to adapt them to the whole needs of the end-users as well as general lighting and energy efficiency, which we obviously must ensure. We must also consider the health and well-being of users as well as their productivity and concentration in workplaces because only with a correct balance between these competencies, some of them in conflict, will we be able to ensure a proper application and evolution of artificial light in human-occupied indoor environments with low natural light access, and provide value-added solutions that contribute to improving people's daily lives in all their aspects and complexity, while ensuring the growth of the lighting business. Otherwise we will have to resign ourselves to an underperforming market with products that do not meet customer expectations. ■

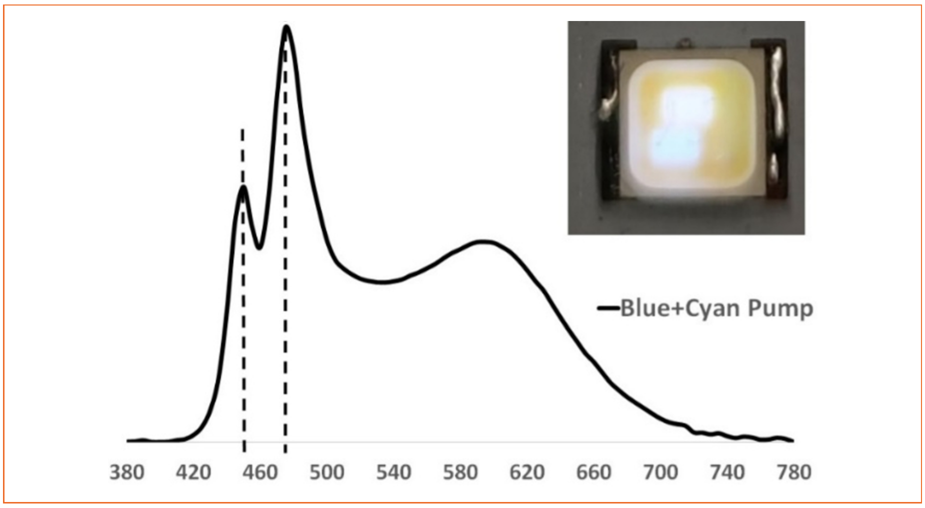

Figure 10: SPD LEDs multi die based on Blue and Cyan Pump.

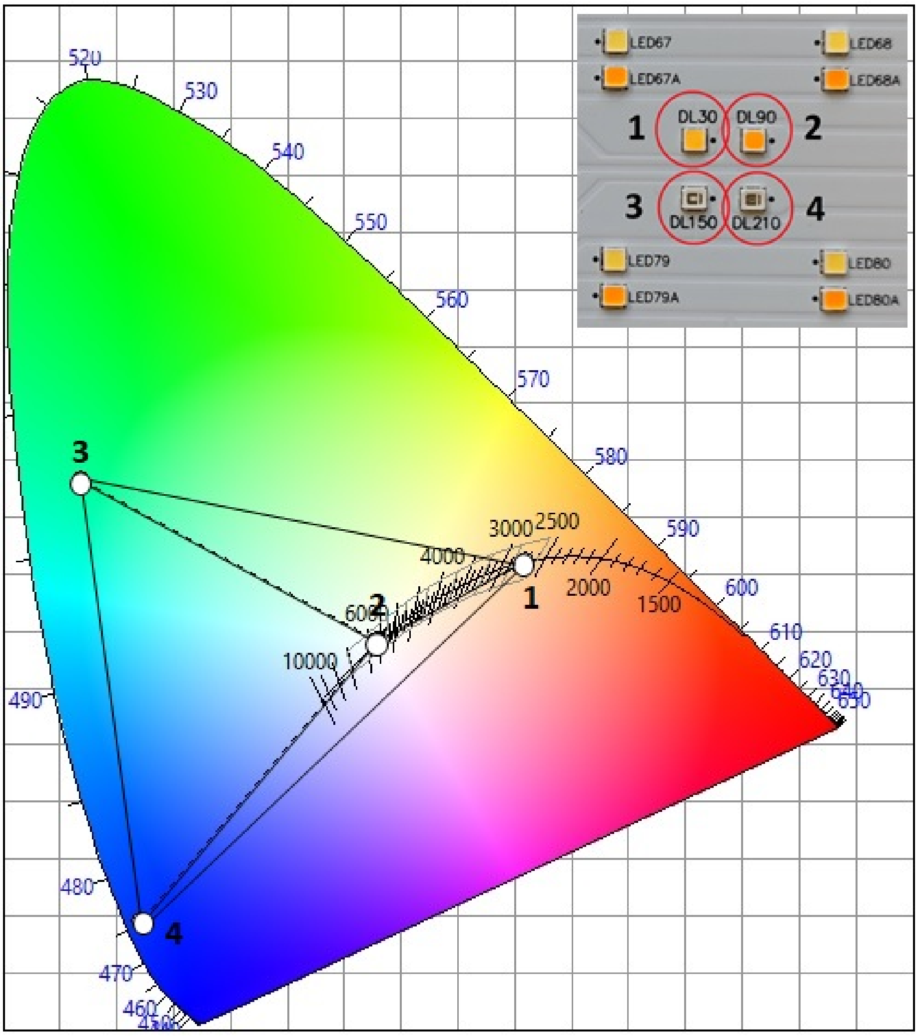

Figure 11: Application based on x4 independent LEDs (CCT 2700 K / CCT 5700 K / Blue λ 480 nm / Cyan λ 500 nm).

AUTHOR: Francesc JORDANA CASAMITJANA

Francesc has an Engineer's Degree (BA) in Industrial Organization, a Technical Engineering Degree (BSc) in Electrical Machines, and a Postgraduate Degree in Statistical Methods. With solid experience in the lighting business, the latter specialized in the design of products and services that add value to the market, improving the environment and the daily life of users thanks to their electrical, optical, and functional features. He has extensive experience in product innovation and development and team management, with extensive knowledge in lighting. He has been working as a technical promoter, laboratory manager, technical manager and innovation director, lighting consultant and technical trainer since 1995.

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DALI-2 and D4i Certification Support Interoperability and Sustainable Lighting

Paul DROSIHN, General Manager of the DALI Alliance

Sometimes you want to go your own way – 'think different' is an appealing slogan. However, it's often best to follow a standard while still leaving room for innovation. Lighting control is no exception. Global standards allow lighting projects to be future-proofed, avoiding proprietary products and vendor lock-in that could prevent a switch to alternative products in the future.

With compatible devices available from multiple sources, customers benefit from long-term confidence in the supply chain. There's no need to throw away your existing systems and start again when you want to make changes, which saves money, and reduces environmental impact.

For decades, lighting-control systems have been using the standardized Digital Addressable Lighting Interface (DALI®) communication protocol, which is now managed by the DALI Alliance, the global industry organization for DALI. Analyst Omdia has described DALI as "the largest wired digital open protocol in the world for lighting." DALI is based on the international IEC 62386 standard, which is split into multiple Parts that can be purchased from the IEC. This openly available family of specifications forms the basis for DALI-based product design. Adding more features and functions to the standardized DALI protocol, the DALI Alliance has created a series of DiiA Specifications that build on and complement IEC 62386. These documents are freely available from the DALI Alliance website, and in future will become new Parts of IEC 62386.

Certification Programs

How can the market be assured that products comply with the requirements described in international standards such as IEC 62386? One approach is for an independent industry organization to establish a product certification scheme. The DALI Alliance was formed primarily to develop such a certification program for DALI-based devices, with a strong focus on building market confidence in the interoperability of products from different vendors.

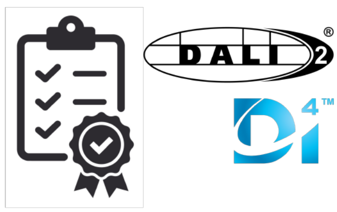


Figure 1: The DALI Alliance runs the DALI-2 and D4i certification programs.

Today, the DALI Alliance runs two related certification programs: the main DALI-2 program, which is based on the latest version of the DALI protocol, and D4i, which enables smart, connected luminaires. In fact, D4i is an extension of DALI-2 for devices with a specific feature set. In turn, D4i enables plug-and-play connector systems and forms the basis of the joint Zhaga-D4i certification program for luminaires and control devices that has been created in collaboration with the Zhaga Consortium. Separately, the DALI Alliance is developing DALI+ certification for DALI devices that operate over wireless and IP-based networks. All of these certification programs are based on the DALI protocol.

The DALI Alliance recently announced that it is strengthening its focus on DALI-2 product certification, including D4i, after ending registration and self-declaration of DALI version-1 control gear. As a standardized platform, DALI-2 mitigates concerns around proprietary technologies and vendor lock-in, and enables future-proof luminaire and system designs for sustainable lighting.

DALI-2 certification requires rigorous product testing, either by the manufacturer or an accredited DALI test house. The DALI-2 tests are defined by the DALI Alliance, building on the requirements of the IEC 62386 standard and related DiiA Specifications. The test results are independently verified by the DALI Alliance, and successful products are certified and listed on the DALI Alliance website. In contrast, DALI version-1 testing was less detailed and relied on self-declaration by the manufacturer, without requiring third-party verification of test results.

DALI-2 certification has matured sufficiently that there is no longer any need to offer a registration scheme for DALI version-1 control gear. All users are encouraged to look for the DALI-2 or D4i logos, which confirm that the product is certified by the DALI Alliance and is fully compliant with the relevant specifications. DALI-2 certification is now available for all control gear types in common use, including those for color control and self-contained emergency lighting, as described below. DALI-2 also includes a broad range of additional features such as storage and reporting of luminaire information and energy and diagnostics data.

DALI version-1 registration was only available for control gear, while DALI-2 certification also includes bus power supplies, and control devices such as application controllers, sensors and other input devices. DALI-2 certification has established an ecosystem of interoperable products, which are all listed in the online Product Database. This contains around 2,500 DALI-2 products of all types, along with over 1,600 DALI version-1 control gear. The DALI version-1 products will remain in the database, and trademark use will continue to be allowed for these devices.

Benefits of Certification

Let's look at the benefits of DALI-2 and D4i certification in a little more detail, and see how they can help lighting project designers and developers. The first role of certification is to indicate that the product complies with the relevant specifications and to ensure that all the DALI features are implemented correctly. Certified products are built on a standardized platform, but of course there is plenty of scope for manufacturers to differentiate.

The detailed and comprehensive DALI-2 tests confirm compliance with the specifications, and are designed to provide high confidence of interoperability with other DALI-2 or D4i devices, including those from different manufacturers. The tests themselves are maintained and updated by the DALI Alliance to incorporate new features and changes to the specifications, and to address any issues encountered during testing.

Independent verification of the test results is both a critical part of DALI-2 certification and a key differentiator from the earlier self-declaration regime of DALI version-1. Listing all certified DALI-2 and D4i products in the Product Database provides traceability, enables customers to check that a product is certified, and prevents false claims of compliance. Successful certification also means that products can carry a DALI-2 or D4i logo, as appropriate, to make it easier for customers to identify interoperable products.

This standardization and certification process has created an ecosystem of lighting-control products from multiple vendors, so customers aren't dependent on a single supplier, or locked into a proprietary technology. While providing customers with more choice, this also encourages competition amongst vendors, leading to a general improvement in products.

DALI is here for the long term: it has been established for decades, and is supported by a growing list of over 300 DALI Alliance members around the globe. As an open, independent organization, the DALI Alliance is able to respond to the evolving needs of the lighting-control market. The DALI-2, D4i and upcoming DALI+ certification programs are all based on the same DALI protocol fundamentals, and backwards compatibility is maintained.

This proven long-term interoperability also improves sustainability and reduces wastage. When you want to upgrade a lighting installation with new components and features, there's no need for a complete retrofit, as could be necessary with proprietary systems. Alternative products can be found if original components are not available or no longer supported. Existing systems can be easily extended, with the freedom to choose from any supplier offering certified DALI-2 or D4i components.

Overall, the standardization provided by DALI ensures that lighting control systems can be future-proof and sustainable, without locking customers into one vendor. This enables systems to develop and expand as new features are added, and can reduce the whole life cost (total cost of ownership) of a lighting project.

Keeping DALI-2 Up-to-Date

Since the first DALI-2 LED drivers were certified almost five years ago, DALI-2 certification has continued to evolve, adding new product types such as sensors, along with new features and functions. Among the most recent additions to the DALI-2 certification program were new options for color control gear, as specified in Part 209 of IEC 62386; such devices are also known as device type 8, or DT8. Other additions included supply voltage controllers for dimmable lamps (Part 205); 0/1-10 V converters (Part 206); and control gear for self-contained emergency lighting (Part 202).

The full list of Parts available for DALI-2 certification is on the DALI Alliance website[3].

DALI enables several alternative methods – known as color types – that can be used to control the color output of LEDs and other light sources. The DALI Alliance recently added DALI-2 tests for LED drivers and other control gear that use two color types, known as RGBWAF and xy. These options sit alongside color type Tc (widely known as tunable white), which was already included in DALI-2.

Color type RGBWAF allows simple control of up to 6 individual channels of color (red, green, blue, white, amber and free color). For more sophisticated control, color type xy allows precise and repeatable selection of the color coordinates from the CIE color space chromaticity diagram. Color type Tc allows control of the correlated color temperature (CCT) along the black-body line, from warm white to cool white. Color types Tc and xy allow calibration of the light-source and control-gear combination, enabling higher color accuracy.

DALI-2 certification is now available for three types of control gear: Tunable White (these are control gear using Tc only); RGB Color Control (RGBWAF only); and Multi-type Color Control (all three color types available in the same product). The first DALI-2 certified product with Multi-type Color Control was the P3K4B1 from ERCO GmbH. This is a PCB-based component that is built into ERCO luminaires, and as such is not sold individually to customers. **Figure 2** shows a luminaire containing the DALI-2 component, as well as an installation showcasing the use of ERCO full color luminaires.

[3]DALI Alliance website: www.dali-alliance.org/dali2/status.html

Figure 2: ERCO has received DALI-2 certification for its P3K4B1 control gear, which is incorporated into ERCO luminaires and offers Multi-type Colour Control (Image © ERCO GmbH / Lukas Palik).

DALI-2 Emergency

For many years, DALI emergency lighting has been widely used for robust, reliable and safety-critical systems in buildings throughout the world. The DALI protocol enables integrated, digital control systems that combine illumination and emergency lighting. Recently, the DALI Alliance added control gear for self-contained emergency lighting to the DALI-2 certification program. For DALI-2, the level of testing has increased dramatically compared with existing DALI emergency control gear, and the results are independently verified, meaning that the industry can have a great deal of confidence in interoperability of devices from different manufacturers.

The first DALI-2 LED driver for emergency lighting was the EM pLED PRO FX 202 LiFePO4 2W SCREW from Tridonic (**Figure 3**).

DALI-2 certification for self-contained emergency control gear is based on Part 202 of IEC 62386, which specifies four device types. The Tridonic device is Type B, meaning that it is maintained, controllable and non-dimmable. Notably, the Tridonic product also implements the DALI data specifications, namely Part 251 (luminaire data), Part 252 (energy data) and Part 253 (diagnostics data). Part 252 allows the energy usage of the emergency LED driver to be monitored and reported.

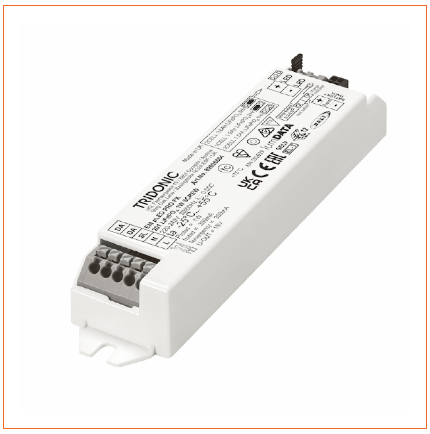


Figure 3: The Tridonic EM pLED PRO FX 202 LiFePO4 2W SCREW from Tridonic was the first DALI-2 certified LED driver for emergency lighting.

Wireless and IP-based Options

As wireless technologies become more widely used in the lighting-control world, the DALI Alliance has looked at ways to combine DALI with wireless networking. Through two distinct approaches, the DALI Alliance seeks to enable suppliers to offer different options according to the lighting scenario and application. One approach is wireless DALI, where DALI commands are carried over a wireless network. The second approach is standardized gateways that effectively translate between DALI networks and existing wireless ecosystems.

Specifications for both these options were published by the DALI Alliance last year [1] and these were later supplemented by Technical Guides[4].

Currently, the DALI Alliance is developing tests to bring two gateway types into the DALI-2 certification program. Certification will be offered for products that function as a DALI-2 application controller and implement either the Part 341 specification for Bluetooth mesh to DALI gateways, or Part 342 for Zigbee to DALI gateways. Of course, the product can also implement other DALI-2 features and functions. In addition, such products will require separate certification (or the equivalent) from the organization responsible for the wireless ecosystem, namely Bluetooth SIG or the Connectivity Standards Alliance for Zigbee gateways.

DALI+ Certification

Gateways will be included in DALI-2 certification, but a different approach is required for wireless DALI. While all DALI-2 and D4i certified devices communicate via a dedicated pair of wires, Part 104 of IEC 62386 describes alternatives to this two-wire DALI bus. In Part 104, DALI commands are carried over other physical media, including both wired and wireless options, as well as

[4] Technical Guides: www.dali-alliance.org/news/342/dali-and-wireless-gateways-explained-in-new-dali-alliance-technical-guides

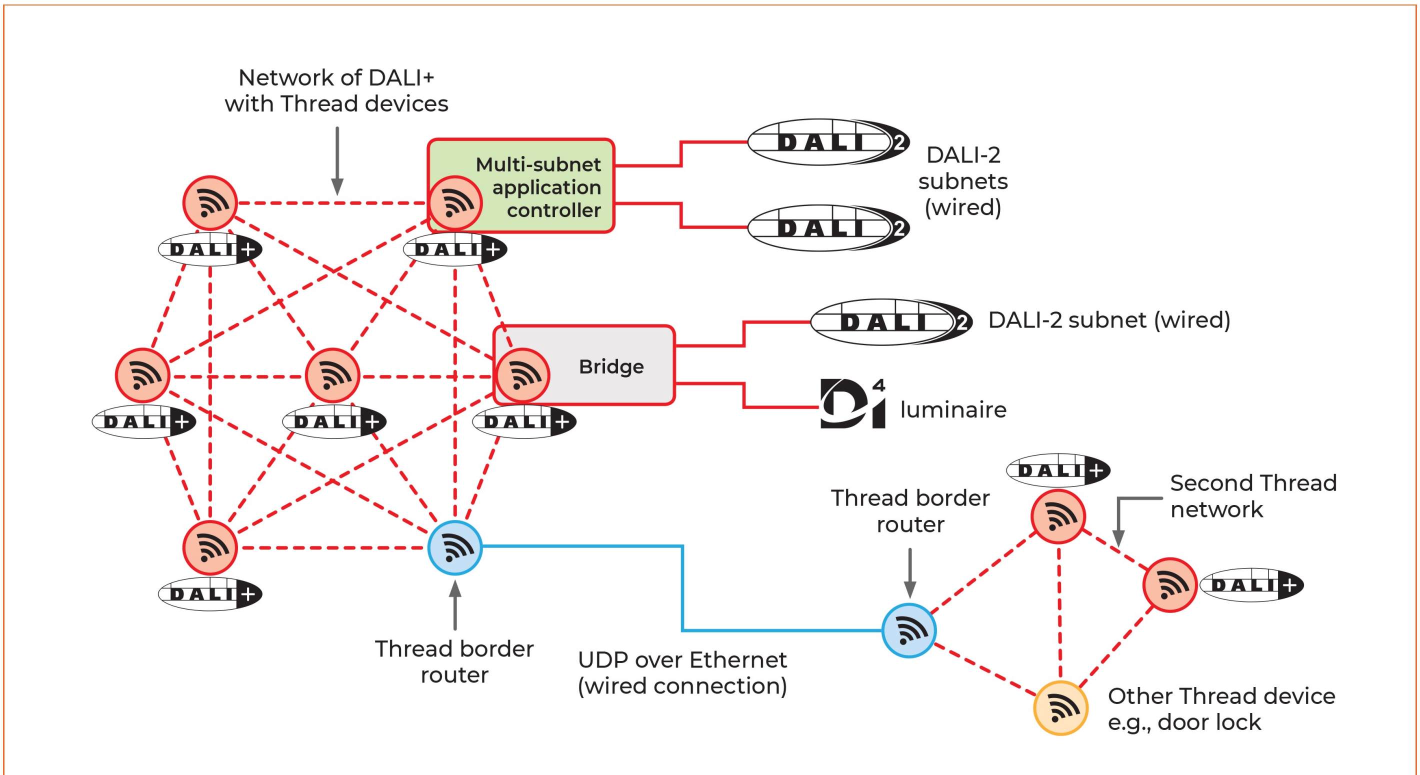


Figure 4: A complex system with connected DALI+ networks and wired DALI-2 and D4i subnets.

the possibility to use Internet Protocol (IP) based carriers.

A new brand, DALI+, was introduced to identify devices that utilize Part 104. DALI+ devices communicate using existing DALI commands, but these are carried over a wireless and/or IP-based medium. DALI+ builds on the proven and sophisticated DALI lighting-control features in wired (DALI-2 and D4i) options, and offers access to the same rich set of data from control gear, luminaires and sensors.

The DALI Alliance is now developing the first certification program for interoperable DALI+ devices, using Thread's low-power, IP-based, wireless-mesh networking protocol as the carrier. Tests are in development to enable "DALI+ with Thread" certification, which will be separate from DALI-2 certification. In future, the DALI Alliance will consider adding DALI+ support for other carriers, and this may include Ethernet (including Power over Ethernet, PoE), Bluetooth mesh and Wi-Fi.

DALI+ enables many connectivity options. **Figure 4** shows an example of a complex system containing several connected DALI+ and wired DALI networks. The application controller at the top of the diagram supports multiple subnets, in this case two wired DALI-2 subnets in addition to the DALI+ network. In the center, a 'bridge' device connects the DALI+ network with both a wired DALI-2 subnet and a D4i luminaire. DALI commands are used throughout, and application controllers in the DALI+ network are able to control, configure and query all of the DALI+, DALI-2 and D4i devices on both sides of the bridge.

This example also shows two wireless Thread networks connected with an Ethernet cable via Thread border routers. The second Thread network contains a non-DALI+ device in the form of a door lock, showing that the Thread network can also support other devices that are not controlled by DALI commands. Furthermore, the system in **Figure 4** could be connected to a larger building-wide IP network.

References

[1] "DALI+ and Wireless to DALI Gateways Increase Connectivity Options for DALI Lighting Networks", LpR 85, May/June 2021, p48.

Conclusions

DALI-2 provides a strong example of a product certification scheme that is built on international standards, and provides market confidence in the interoperability of products from different vendors. In turn, this ensures that lighting control systems can be future-proof and sustainable, without locking customers into a single vendor. The integrity of certification is maintained by an open, independent organization that responds to the needs of the international lighting community. ■

Author: Paul DROSIHN

Mr. DROSIHN was appointed as General Manager of the DALI Alliance in May 2019. Paul is a highly qualified and experienced management professional with more than 30 years' experience in the electronics and LED lighting industries. He has held senior roles in management, sales, operations, business development and strategic marketing, at companies involved in electronics distribution, semiconductor manufacturing, precision optics manufacturing and management consulting. He is a Member of IEEE and AMBA, and a Fellow of the Institute of Leadership and Management.

About DALI Alliance
The DALI Alliance (also known as the Digital Illumination Interface Alliance or DiiA) is an open, global consortium of lighting companies that drives the growth of lighting control solutions based on internationally standardized Digital Addressable Lighting Interface (DALI) technology. The organization operates the DALI-2 and D4i certification programs to boost levels of cross-vendor interoperability. As lighting continues to evolve and converge with the IoT, the DALI Alliance is also driving the standardization of wireless and IP-based connectivity solutions. Website: www-dali-alliance.org

Good Light for a Healthier and Happier Life

Jan DENNEMAN, Chairman Good Light Group

Scientific studies from recent decades show very clearly that light is crucial for our health and well-being. Good light is as important as good food and good exercise.

We live most of the time indoors, shielded from the power of daylight. This negatively influences our sleep quality, energy level and mood. We need more Good Light during the day and less light at night. This will have a positive influence on our health and well-being. It tells our brain what time of day it is, and gives us more daytime energy and makes us sleep better at night.

If you want to enjoy a better sleep, get your daily dose of "vitamin-L". We developed a four step approach. Make sure that during the day, your eyes get enough light, at least 1000 lux for a couple of hours.

Did You Know Most People Live and Work with Insufficient Light?

You might be one of them!

See **Illustration A**.

Homo Sapiens mostly lived outdoors for tens of thousands of years. This was because they needed to collect and hunt for food. Like all other living species on earth that live outdoors, they were exposed to daylight. Over the last 300 years, however, mankind has moved increasingly indoors. Especially after the industrial revolution there was little reason to be outdoors anymore. Today we spend more than 90% of our lives indoors. Shielded from nature and especially shielded from daylight. This is an unnatural situation for our bodies and brains to be in.

See **Illustration B**.

Good Light has an enormous positive influence on how well we sleep, our energy level during daytime and our mood.

See **Illustration C**.

Nowadays, people are always in dark houses, factories, schools, hospitals, universities, care centers, shops and restaurants, etc., during the day.

Our Bodies Need Light!

Getting enough light is an important ingredient for **good health**.

See **Illustration D**.

People understand that light is important for us to be able to see. However, most people are not aware that light also tells our brain what time of day it is. It helps to synchronize the master clock in our brains. However, the light levels indoors are too weak to trigger the master clock properly. We live on an earth with a 24 hour light-dark cycle and a social clock that also has a 24 hour rhythm. But our bodies are not synchronized, and this leads to negative consequences for sleep quality, energy, mood and health. We need more good light during the day and less light at night.

See **Illustration E**.

Light is the main "Zeitgeber". The daily light-dark cycle affects the rhythms of our body. Light is the most important factor in keeping our biological clock in sync with the 24-hour day.

See **Illustration F**.

Most people understand the importance of good food, good air and good exercise. They know that these things all have a positive effect on their wellbeing and health. They are unaware, though, that good light is also crucial for a healthy and happy life. Good light is as important as good food! But how can you get your daily dose of "Vitamin-L"?

Get Your Daily Dose of "Vitamin-L"

There are four steps to bring good light or Vitamin-L into your life.

See **Illustration G**. See **Illustration H**.

The first step is becoming aware of the light you are in throughout the day. Buy a light meter or install a light meter app on your smart phone. You'll soon discover that the outdoor light levels are fifty to hundred times higher than indoors. It is especially important to measure the light entering your eyes.

Move your desk within one meter of a window. If this is not possible, use electric light that generates 1000 lux that will enter your eyes.

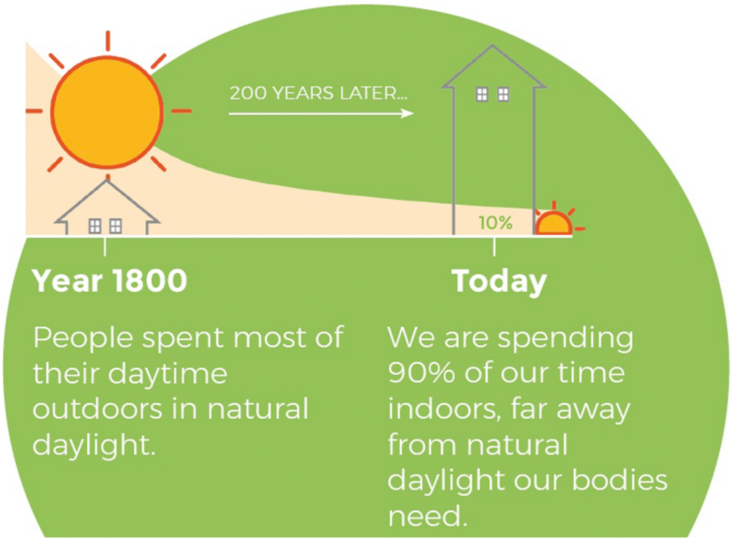
See **Illustration I**.

The third step is to live by the 20-20-2 rule. Make a habit of, after every 20 minutes of concentrated work, walking over to a window and looking at the sky for 20 seconds. Make sure you spend 2 hours outdoors every day – preferably in the morning.

See **Illustration J**.

Many people have sleeping problems. Unfortunately, they don't make the connection between their lack of sleep and their distorted circadian rhythm. Remember, good light is better and has less complications than taking sleeping pills. ■

Author: Jan DENNEMAN
Jan Denneman is the Founder and Chairman of the Board of the Good Light Group as well as Honorary Ambassador of the Global Lighting Association. The Good Light Group is a non-profit organization that promotes the use of Good Light indoors. Good light is daylight or electric light with comparable beneficial effects. Jan has more than 40 years of experience in executive roles in sustainability, innovation and business development and has held senior innovation and marketing roles at Philips Lighting (now Signify) during the industry's transition to LED and Intelligent Lighting Systems. He founded several international consortia, such as the Global Lighting Association, Zhaga Alliance, the Connected Lighting Alliance and LightingEurope. Jan was President of the Global Lighting Association from 2007–2017 and President of LightingEurope from 2013–2017.



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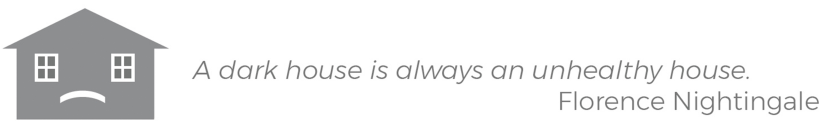

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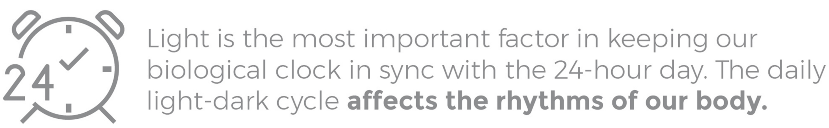

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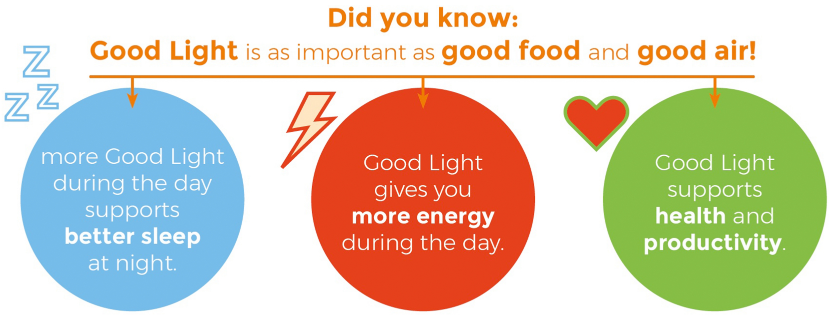

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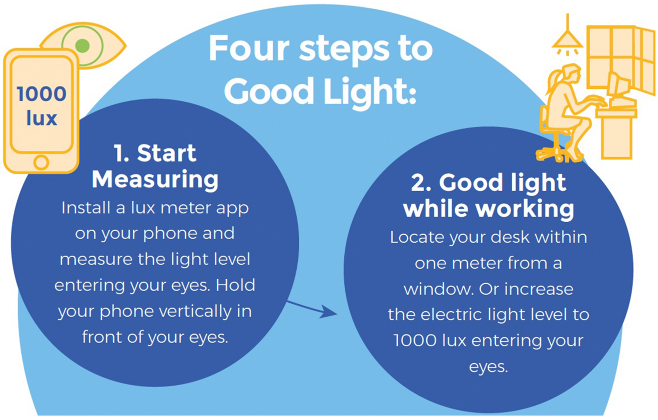

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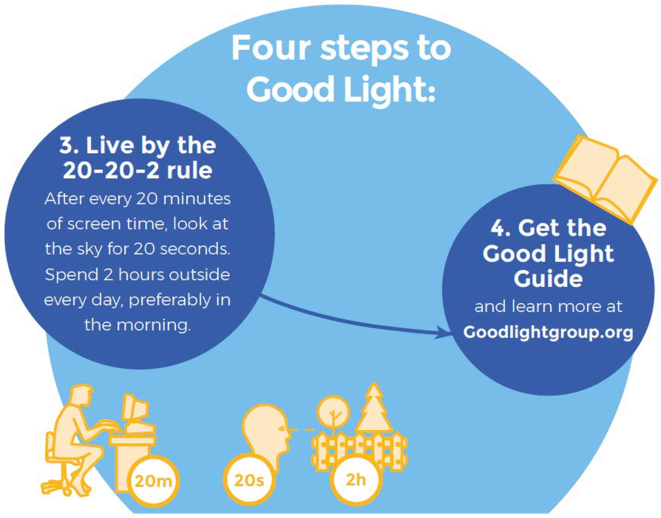

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The **Good Light Group** is a non-profit organisation that promotes the health and well-being effects of Good Light. If you support our activities and want to join as participant, let's get in touch!

info@GoodLightGroup.org

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