LED professional Review

www.led-professional.com

ISSN 1993-890X

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The Global Information Hub for Lighting Technologies and Design

Jan/Feb 2022 | Issue 89

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LpS Digital Awards

In December 2021, the LpS Digital Awards, highlighting the focus of the previous year, were presented. Those highlights, which I will pick up on below, will help guide us through the coming year.

The award winners are named separately in this issue's Lighting News.

Lighting designs and solutions are increasingly being designed and developed according to sustainability and the circular economy. Lighting technologies focus even more on spectral optimizations to stimulate human needs. These solutions, known under the category of Human-Centric Lighting, are also referred to as integrative lighting, because the designs influence or control lighting and physiological effects. New lighting technologies also enable the resolving of the contradiction between efficacy and CRI, thus allowing more freedom for optimal lighting designs. Of course, light is also used to combat viruses, and with UV-C solutions, we expect to see even more exciting concepts on the market.

Digitalization continues to advance rapidly. Seeing light as a data carrier of information and talking about platforms instead of modules, shows, for example, the developments in the field of LiFi, which open up entirely new possibilities.

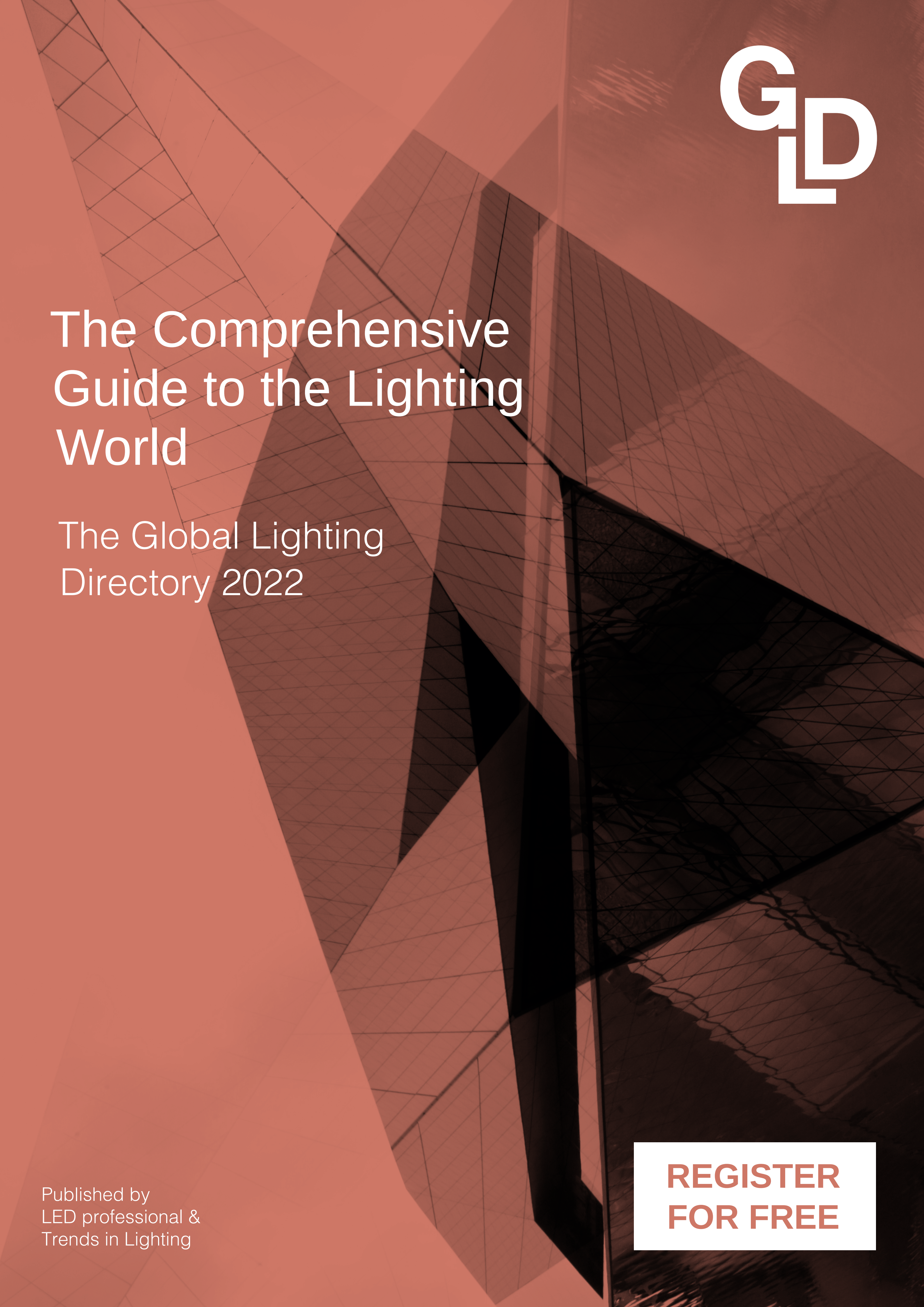
The LpS Digital Awards are certainly not all-encompassing, but they highlight the lighting sector's main focal points this year.

We hope this issue offers many new impulses for you and, above all, that you enjoy reading it. It contains the points mentioned above, including an in depth interview with the founder of LiFi, Professor Harald Haas.

Yours Sincerely,

Siegfried Luger

Luger Research e.U., Founder & CEO
LED professional, Trends in Lighting, LpS Digital & Global Lighting Directory
Photonics21, Member of the Board of Stakeholders
International Solid-State Lighting Alliance (ISA), Member of the Board of Advisors
Member of the Good Light Group and the European Photonics Industry Consortium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ADVERTISING INDEX

Ourania GEORGOUTSAKOU

Ourania Georgoutsakou is the Secretary General of LightingEurope, the voice of the lighting industry in Brussels. Ourania joined LightingEurope in April 2017 and is responsible for LightingEurope's strategy and impact. Her role is to represent Europe's lighting industry in the Brussels political arena, liaise with industry executives and manage the association's operations.

She has over 15-years' experience of advocating for membership associations, previously working as Director of Public Policy in Europe for SEMI and as Senior Policy Coordinator with the Assembly of European Regions in Strasbourg and in Brussels.

Shaping the Future of the Lighting Industry Together

The past two years have brought an extra touch of complexity to all our lives, especially when it comes to planning, but the only way to go remains forward.

In 2022 Europe's lighting industry will be asked to speak with a single voice on where we want to be in a few years' time.

The policies and rules that will be decided in Europe over the next 2–3 years will have a direct impact on how lighting products are designed, manufactured and sold on the European market. They are the opportunity to support and accelerate the delivery of our vision to increase the value of lighting for people, for the planet and for the lighting value chain.

"The rules and requirements that will come are a rare opportunity to shape the future of our industry for the next 10+ years."

OURANIA GEORGOUTSAKOU

Make no mistake – the rules and requirements that will come are a rare opportunity to shape the future of our industry for the next 10+ years. If you think about it, we've been on the edge of something new for a while now. What people think is important and what they want is changing. How institutions, governments and companies are perceived and what their role should be is evolving, with increased talk about living in a post-democracy and post-facts world. Resilience to cyber, environmental and health threats is now a priority. The current pandemic has further disrupted established patterns, including in our global supply chains.

Someone did say "never waste a good crisis".

And thus we are privileged to stand on the edge of this "something new", a potential paradigm shift in our economies, our governance structures, our international trading relationships, and to be part of shaping the future of the lighting industry together.

To give you a taste of what's in stock for LightingEurope this new year:

⇒ We have a shortlist of 22 draft EU laws or policies that will be published or voted on in 2022. We expect at least 8 draft texts on sustainable products by the end of Q1, most likely addressing circular product design, repair & reuse, environmental declarations, substantiating green claims and more. Existing business models are also up for discussion, with incentives for "products as a service" and possible obligations to maintain, refurbish or remanufacture products.

⇒ While many companies are still getting to grips with the new ecodesign and energy labelling requirements for light sources and the EU EPREL database – if you don't know what I'm talking about, check out the LightingEurope Guidelines on our website – in LightingEurope we are preparing the next generation of legislation post-2024. The current rules contain a list of possible additional requirements that could be introduced. As an industry we should also review the scope of the legislation and make recommendations on how to set rules that companies can understand and apply and that authorities can check and enforce.

⇒ New policies are bringing new opportunities for various applications. There's increased momentum for buildings renovation and an interest in connected systems, that will be accelerated by the next wave of EU phase outs of conventional lighting over the next three years. In the agriculture and food sector there's a search for alternatives to pesticides or to using chemicals and packaging for food preservation methods. UV disinfection technologies are increasingly perceived as a reliable option to allow us to again co-exist in safe healthy spaces. ■

O.G.

Wireless control for emergency lighting

A simple route to modern lighting infrastructures: benefit from emergency lighting controlled by HubSense®.

When the main power supply fails, it's emergency lighting that provides light in buildings, such as schools or offices. Of course, it is a critical feature mandated by various building regulations. In some cases these emergency systems are self-contained, which means the luminaires are connected to the main power supply. In the event of an emergency, each luminaire switches over to a battery located within the luminaire itself.

This is exactly where OSRAM comes in. The new QBM DALI EL-T CONV transforms existing DALI emergency luminaires into wireless ones, controlled by OSRAM's smart lighting control system HubSense®. HubSense® is based on the standard protocol made by Bluetooth SIG.

With HubSense®, you no longer need to rely on hybrid or complicated proprietary systems. Emergency l uminaires equipped with the QBM DALI EL-T CONV can be easily integrated as a regular node in the HubSense® ecosystem. This gives you and your clients the full advantage of a modern lighting infrastructure. Most importantly, by integrating the QBM DALI EL-T CONV you can renovate and upgrade entire existing installations – both regular and emergency lighting.

In addition to modernizing emergency lighting, our new device also streamlines both functional tests and duration tests, which are mandatory by law. Tests are scheduled or triggered manually by the facility manager. Results and reports can be collected on-site and saved on mobile devices, then distributed by e-mail. The generated report lists exactly which luminaries were tested and indicates whether there is a fault. Maintenance of the lighting systems can always be carried out immediately and accurately.

By transforming existing DALI emergency luminaires into smart ones, all controlled by one system, the QBM DALI EL-T CONV permits you to renovate lighting installations in every European market.

By introducing the QBM DALI EL-T CONV, OSRAM now offers a standalone solution for emergency lighting testing, reporting and maintenance. With it you can rely on a modern lighting infrastructure that is future-proof and scalable.

Dennis Fullin

Dennis Fullin is Senior Product Manager at OSRAM and an expert on HubSense®, a wireless lighting control system. After earning a master's degree in electronic engineering, he started in OSRAM's Automotive Department as Project Manager. Today, he successfully manages LED driver and lighting control portfolios. He's curious about technological advancements in the sector and committed to delivering the right technology for his clients' projects.

Smarter lighting with HubSense

Flexible, wireless and easy to install: OSRAM's HubSense® is the new standard for modern lighting systems:

- lighting control is wireless and uses a standard protocol
- installation is clean, fast and cost-competitive
- lighting upgrades involve only the installation of new, radio-controlled luminaires, sensors and control elements
- no need for masonry work
- scalable and easily expandable

To find out more about the new QBM DALI Emergency Test converter, reach out to the team at OSRAM DS here: **www.osram.com/hubsense**

Light is OSRAM

OSRAM

LPS DIGITAL AWARDS 2021

In December, the LpS Digital 2021 Award winners were announced and honored during the annual live-stream event on December 2nd. The four areas recognized were: Best Lectures, Sustainability, Scientific Study and Best Products. The most outstanding contributions and solutions from the past year were honored. The awards covered the subject areas of LED Technologies, HCL, UV-C, LiFi, and Circular Economy.

LECTURE AWARD

Mikolaj PRZYBYLA
"Introduction to UV Light Measurement Principles, How to Measure UV LEDs Correctly"

Mikolaj PRZYBYLA: Chief Operation Officer, GL Optic, CIE and IES Member

The jury distinguishes this lecture as the most recognized presentation on LpS Digital (1,500+). Reliable UV radiation measurements are the foundation for every UV light disinfection system. ■

View the lecture on LpS Digital.

LECTURE AWARD

Xavier DENIS
"ipRGC Sensitive Optimized LED Spectrum and Its Application in Color Tunable Lighting Solutions"

Xavier DENIS: Technical Marketing Manager, Nichia Europe

The jury distinguishes this lecture as an important stimulus and technology step for human-centric / integrative lighting designs. The Cyan LED technology, based on SAE phosphors, is introduced. ■

View the lecture on LpS Digital.

LECTURE AWARD

Musa UNMEHOPA
"The Future Potential of LiFi – Light Fidelity – Is Here Today"

Musa UNMEHOPA: Head of Ecosystems and Strategic Alliances, Signify

The jury distinguishes this lecture as an important stimulus for light communication technologies and its market penetration. The lecture highlights LiFiecosystem, LiFi standardization and focuses on market/application opportunities. ■

View the lecture on LpS Digital.

LECTURE & SUSTAINABILITY AWARD

Mark RIDLER
"Overview of Circular Economy Approaches in Lighting Design and Projects"

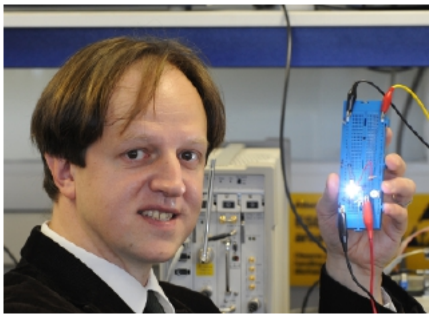
Mark RIDLER: Head of Lighting, BDP

The jury distinguishes this lecture as an important stimulus for sustainable lighting design. The presentation shows a comprehensive picture of Circular Economy in Lighting Design joined with results from research, practice and the broad expertise of the author. In addition to the lecture, a supplementary interview on the topic of sustainability was made. ■

View the lecture on LpS Digital.

SCIENTIFIC LECTURE AWARD

Harald HAAS
"LiFi, The Catalyst for New LED Applications"



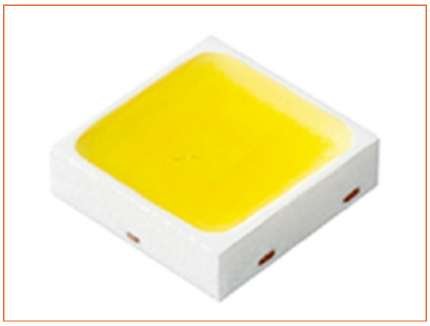
Harald HAAS: Professor, Univ. of Strathclyde

Prof. Haas illustrates the background for his LiFi research – the need for higher bandwidth to match the continuously growing communication data volume. He gives an overview of ongoing experimental research, focussing on open challenges and achieved results. Finally, he gives a perspective on what LiFi could mean for the lighting industry. ■

View the lecture on LpS Digital.

PRODUCT AWARD

H6 LED Series
"LED Technology that Combines High Efficacy and High CRI in One Product"



H6 LED Series

The jury distinguishes this product as a breakthrough to improve high-quality smart lighting solutions and contribute to sustainable lighting designs. The H6 series takes advantage of a unique red narrow band phosphor technology. Lighting professionals no longer have to choose between high color rendering and high efficacy. ■

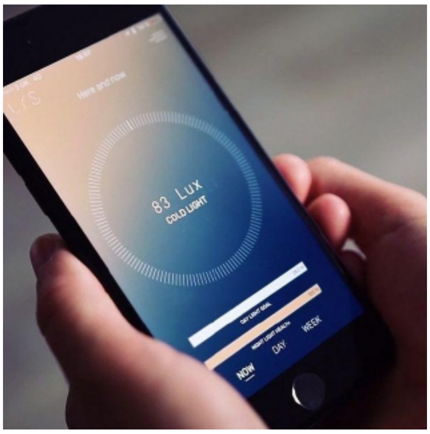
View the product presentation on LpS Digital.

About NICHIA Corporation
Having 'Ever Researching for a Brighter World' as a motto, NICHIA takes great pride in being the technology leader and world's largest LED manufacturer. Founded in 1956 as a specialist chemical producer, NICHIA quickly became the leader in luminescent materials (phosphors). Nichia later developed and commercialized the first high brightness blue LED in 1993 and the first white LED in 1996. Additional nitride-based LEDs in various colors were developed, including ultraviolet and visible laser diodes. NICHIA believes that its products will remain at the forefront of energy efficient solutions throughout the world for years to come. NICHIA will continue to be a company that makes contributions to the world by evolving its original and unique technologies and 'Ever Researching for a Brighter World'.
`https://www.nichia.co.jp/en/about_nichia/index.html`

PRODUCT AWARD

LYS
"Live Healthier with Light"

LYS Button, a wearable light sensor.



LYS In-app coaching designed with leading experts.

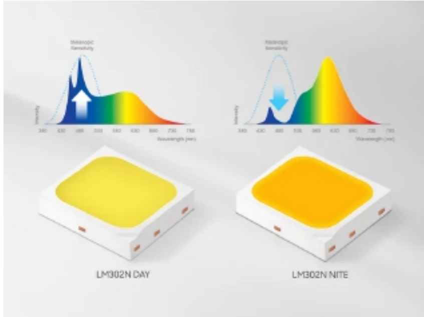
The jury distinguishes this system solution as an important contribution to stimulate better light, light quality and health improvement through light. People can track their light exposure and understand light's impact on sleep and energy. Improve overall sleep, wellbeing and productivity through the LYS Light Diet program based on smart- and cloud-based technologies. ■

View the product presentation on LpS Digital.

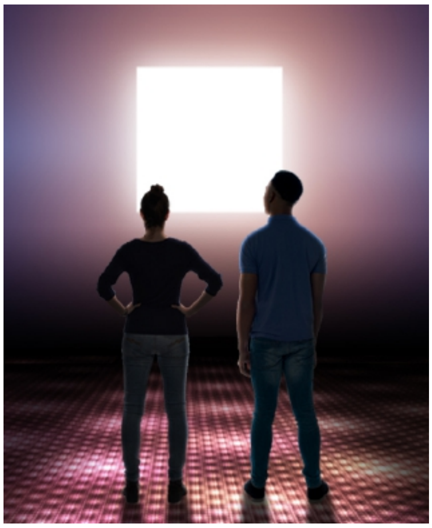
About LYS Technologies
Founded by an innovation designer and a biomedical engineer, LYS combines a human understanding for good design with evidence-based technology. What began as a Kickstarter in 2016 has grown to global, award-winning business. LYS can now be found in 53 countries worldwide, from Nuiqsut, Alaska all the way to our southernmost user in Christchurch, New Zealand. Although LYS might just be the next big breakthrough in human-centric lighting, LYS stays true to their simple calling which is to make healthy light available to everyone.
`https://lystechnologies.io`

PRODUCT AWARD

HCL LED Series
"Each Place Has Its Own Purpose, Complete it with the Right Light"



HCL LED Series



The jury distinguishes this product family (LM302N DAY, LM302N NITE) as an essential contribution to health and wellbeing. Furthermore, Elio Jin-Ha KIM explains the topic of HCL in his outstanding webinar, which also includes an actual spectra measurement demonstration on different lighting conditions. ■

View the product presentation on LpS Digital.

About Samsung
Samsung Group engages in the manufacturing and selling of electronics and computer peripherals. The company operates through following business divisions: Consumer Electronics, Information Technology & Mobile Communications and Device Solutions. The Device Solutions business division comprises of memory, system large scale integrated circuit and light emitting diode. The company was founded on January 13, 1969 and is headquartered in Suwon, South Korea.
`https://www.samsung.com`

BUSINESS NEWS

LED Lighting Development Wins 2021 Queen Elizabeth Prize for Engineering (QEPrize)

Shuji Nakamura, Prince Charles, Dr. Kazuaki Takahashi, Lord Browne, Russel Dupuis, Dame Lynn Gladden; left to right, back to front (Photo credit: Image courtesy of the QEPrize).

The 2021 QEPrize is awarded for the creation and development of LED lighting, which forms the basis of all solid state lighting technology. Isamu Akasaki, Shuji Nakamura, Nick Holonyak Jr, M. George Craford and Russell Dupuis are recognised not only for the global impact of LED and solid state lighting but also for the tremendous contribution the technology has made, and will continue to make, to reducing energy consumption and addressing climate change.

First awarded in 2013 in the name of Her Majesty The Queen, the QEPrize exists to celebrate ground-breaking innovation in engineering. The 2021 winners are announced today by Lord Browne of Madingley, Chairman of the Queen Elizabeth Prize for Engineering Foundation. HRH The Princess Royal shared a message of congratulation for the winners.

Solid state lighting technology has changed how we illuminate our world. It can be found everywhere from digital displays and computer screens to handheld laser pointers, automobile headlights and traffic lights. Today's high-performance LEDs are used in efficient solid state lighting products across the world and are contributing to the sustainable development of world economies by reducing energy consumption.

Visible LEDs are now a global industry predicted to be worth over $108 billion by 2025 through low cost, high efficiency lighting. LED lighting is 75% more energy efficient than traditional incandescent and compact fluorescent bulbs, and is playing a crucial role in reducing carbon dioxide emissions. LED bulbs last 25 times longer than incandescent bulbs and their large-scale use reduces the energy demand required to cool buildings. For this, they are often referred to as the 'green revolution' within lighting.

"Engineering is imperative to solving human problems. All over the world, everyone knows the QEPrize. Most importantly, this is a team prize. I was able to do what I did in the 1980s, because of what had come before. When I was modifying reactors every morning and every afternoon continuously for a year and a half, I never thought it would be so successful." Professor Shuji Nakamura

"This is a really special moment for me. The QEPrize is so prestigious and it is spectacular to receive recognition from The Royal Family. It is a career highlight that is impossible to beat. Engineering is incredible, and I am proud to part of something that has made such a big impact on the world." Dr George Craford

"It is really something to share in this award win among my friends and colleagues – all five of us each played an important role, and this recognition means an awful lot. In those early days, when it was long days and nights hand-building reactors, Nick Holonyak mentored us. He really drew us in and inspired us to be part of the adventure that is engineering." Professor Russell Dupuis

"This year's Prize winners have not only helped humanity to achieve a greater degree of mastery over the environment, they have enabled us to do so in a sustainable way. They have created a product which we now take for granted, but which will play a major role in ensuring that humanity can live in harmony with nature for many more centuries to come." Lord Browne of Madingley, Chairman, Queen Elizabeth Prize for Engineering Foundation

"The impact of this innovation is not to be understated. It makes lighting a lot cheaper and more accessible for emerging economies. For example, LEDs are being used on fishing boats where previously the only option would have been paraffin lamps. They are much cheaper and safer. It is not only an extreme engineering achievement, but a societal impact that has a significant impact on the environment." Professor Sir Christopher Snowden, Chair of the QEPrize Judging Panel

The winners were formally honoured at the QEPrize ceremony. They received the £1 million prize and an iconic trophy, designed by the 2021 Create the Trophy winner Hannah Goldsmith, a 20-year-old design student from the United Kingdom.

Lord Browne also announced a change in the QEPrize cycle to reflect the fact that just as engineering is continually evolving so too is the QEPrize, which will now be awarded on an annual basis. The increase in the frequency of the prize cycle will offer greater opportunities to recognise engineering excellence.

Regarding this change Lord Browne said, "At the Queen Elizabeth Prize for Engineering, we recognise that a new age of innovation demands a new approach. As engineering and its place in society keep evolving, so too must the Prize. We want to expand our horizons, and do more to recognise the diversity of contemporary engineering."

"I cannot think of a better way to honour what has been an extraordinary year for engineering, and to celebrate the centrality of engineers to the story of human progress." ■

Signify to Acquire Fluence to Strengthen Agriculture Lighting Growth Platform

Signify announced that it has entered into a definitive agreement with ams OSRAM (SIX: AMS) to acquire Austin, Texas based Fluence for USD 272 million (EUR 242 million) on a cash and debt-free basis. This acquisition will strengthen our global Agriculture lighting growth platform and extend our position in the attractive North American horticultural lighting market. The acquisition is fully in line with our strategy to expand in attractive growth segments and our commitment to improving food availability by providing growers with horticultural lighting that helps them to reduce resource consumption and increase yields. We expect the global market for agricultural lighting to grow by more than 20% per year to EUR 1.6 billion in 2024.

The acquisition will add Fluence's complementary horticultural lighting technology to our existing knowledge and expertise. This includes light recipes for the legal growing of cannabis (1* see footnote) – which, due to the legalization in Canada and many US states in recent years, currently generates the majority of Fluence's sales – and light recipes for the company's fast-growing business to grow other crops. Fluence's technology also includes more than 140 issued and pending patents, focusing on areas such as light quality, thermal management and installation methods. Currently Fluence generates a majority of its sales in North America.

"We're excited to announce that we're acquiring Fluence, strengthening our agricultural lighting business, one of our main growth platforms. It also further underlines the strategic importance of the North American market to our business," said Harsh Chitale, Division Leader Digital Solutions at Signify.

"We're looking forward to welcoming the team from Fluence. Its lighting innovations and solid go-tomarket strategy have helped build a recognized brand with a strong position in North America and a fast-growing business in Europe. We feel that now is the right moment to join forces, allowing both of us to serve more customers with high-quality horticulture lighting products."

"Since Fluence's founding, it has been our sole mission to improve the interaction between light and life to yield a healthier and more sustainable world. Adding our lighting solutions to Signify's strong portfolio empowers our combined businesses to deliver the world's most advanced horticulture technology to cultivators on a global scale," said David Cohen, CEO of Fluence. "The combination of our companies will immediately expand our collective footprints and inject valuable expertise into both companies' product innovations. We look forward to uniting with the Signify team."

Fluence employs more than 200 people. In the trailing 12 months (October 2020 to September 2021), Fluence generated USD 141 million (EUR 124 million) in revenue. Fluence will operate as an entity within Signify's agricultural lighting business in Division Digital Solutions. The acquisition is expected to close in the first half of 2022, subject to regulatory approvals and other conditions.

1*) Signify and Fluence share a similar policy to only provide lighting products for the cannabis industry to growers that are legally permitted to do so, including markets that permit growing for recreational use. Fluence abides by and respects local laws and does not provide lighting for cannabis production in geographies in which it is not permitted. ■

SchahlLED Lighting Acquires LED Technics Germany

Carsten Weber, Sales Director SchahlLED; Andreas Kreuss, CEO LED Technics Germany; Erich Obermeyer, Business Manager SchahlLED; Bernd von Doering, Business Manager SchahlLED

SchahlLED Lighting GmbH acquires LED Technics Germany GmbH (LTG). SchahlLED is a leading provider of intelligent digital lighting solutions for industry and logistics based in Unterschleißheim. LED Technics Germany manufactures highly efficient, user-friendly LED lighting for medium-sized businesses. The LTG brand will continue to exist alongside SchahlLED, optimally augmenting SchahlLED's product portfolio. Going forward, customers will have access to controlled and uncontrolled solutions from both brands, and can choose to optimize LTG Systems with SchahlLED controlling solutions.

"LED Technics Germany is a perfect fit for our ambitious growth strategy," says Bernd von Doering, managing director at SchahlLED. "Together, we can offer intelligent, cutting-edge LED lighting solutions for the industrial and logistics sectors." LTG's business model is also a strategic match: The companies' network of direct and digital sales channels is a fit for SchahlLEDs long-term goals focused on sustainability through lower energy consumption and the development of intelligent solutions.

"We have worked together closely in the past, and discovered that we share core values like passion, commitment and a hands-on mentality", says Andreas Kreuss, who will continue to lead LED Technics Germany as managing director and additionally develop SchahlLED's sales network in western Germany. Mr. Kreuss founded LTG twelve years ago and has lead the company since. "I'm proud that our development as a company has put us on the map for such a strong partner, and look forward to join forces with SchahlLED in developing even better intelligent digital lighting solutions."

About LED Technics Germany GmbH
LED Technics Germany was founded in 2009 and develops high-end and energy-efficient lighting solutions for industry and business customers. The Cologne-based company's LED systems provide medium-sized businesses with affordable, user-friendly lighting solutions that reduce energy consumption. With a background in electrical engineering, founder and managing director Andreas Kreuss emphasizes tailor-made lighting solutions that are especially easy to implement. LED Technics Germany serves medium-sized companies from all over Germany, and has a strong presence in the Rhineland region. Customers include Cologne Bonn Airport, Dextro Energy, Gottfried Schultz SE, Borbet GmbH and many more. For more information, visit www.led-technics-germany.de

About SchahlLED Lighting GmbH
SchahlLED is a turnkey service provider of intelligent LED solutions for the industrial and logistics sectors with more than 50 years of lighting and 20 years of LED experience. The company is based in Unterschleißheim near Munich and is active in Germany, Austria, Switzerland and Poland. As both manufacturer and full-service provider, SchahlLED plans lighting concepts and supplies intelligent LED lighting systems. With an extensive network of sales and service partners in Germany, Austria, Switzerland and Poland, SchahlLED completes more than one hundred projects annually. For more information, visit www.schahlled.de. ■

Faraday Future Announces HSL as Exterior Lighting Supplier

Faraday Future Intelligent Electric Inc., a California-based global shared intelligent electric mobility ecosystem company, announced HSL as the lead exterior lighting supplier for its flagship, ultimate intelligent techluxury FF 91 EV.

HSL srl. supplies intelligent lighting systems and high-performance components for leading exclusive car brands worldwide. With its agile manufacturing, HSL enables fast market entries with a strong focus on individualization and technical perfection. Equipped with knowledgeable automotive veterans that cover every facet of exterior lighting, HSL will work with FF throughout the production process to ensure a premium and innovative exterior lighting display.

"The exterior lights play a key role in the vehicle's overall aesthetic, which is why we partnered with a distinguished supplier that has deep experience in premium exterior lighting," said Page Beermann, Design Director at Faraday Future. "Details such as the FF 91's rear 3D crystal-like array tend to be one of the last things finished in a car development program, but is one of the first things customers notice."

HSL will supply the Exterior Lighting for the FF 91. Complementing the future-forward design of the vehicle, the rear of the FF 91 will display a unique, 3D crystal-like array that stands apart from anything else on the road. Additionally, each individual LED is programmable, enabling customized lighting animations that can be uploaded to the vehicle at any time, with preset animations available at launch.

"Outfitting the FF 91 with our premium and innovative exterior lighting ensures its unique position among top luxury vehicles," said Mirko Bonvecchio, CTO at HSL. "The future forward design and the possible personalization of the lighting design is outstanding."

HSL's experience and commitment to the FF 91 program will contribute to the on-schedule delivery of the vehicle in July 2022. The FF 91 Futurist Alliance Edition and FF 91 Futurist models represent the next generation of intelligent, internet-driven electric vehicles (EV). They are high-performance EVs, all-ability cars, and ultimate robotic vehicles, allowing users to experience the third internet living space. The models also encompass extreme technology, an ultimate user experience and a complete ecosystem.

Users can reserve an FF 91 Futurist model now via the FF intelligent APP or FF.com at: https://www.ff.com/us/reserve.

About Faraday Future
Established in May 2014, Faraday Future is a global shared intelligent mobility ecosystem company, headquartered in Los Angeles, California. Since its inception, Faraday Future has implemented numerous innovations relating to its products, technology, business model, profit model, user ecosystem, and governance structure. On July 22, 2021, Faraday Future was listed on NASDAQ with the new company name "Faraday Future Intelligent Electric Inc.", and the ticker symbols "FFIE" for its Class A common stock and "FFIEW" for its warrants. The "I" in FFIE stands for Intelligent and Internet and the "E" stands for Ecosystem and Electric. FF is not just an EV company, but also an internet and technology company, an AI product company, a software company, and a user ecosystem company. Faraday Future aims to perpetually improve the way people move by creating a forward-thinking mobility ecosystem that integrates clean energy, AI, the Internet and new usership models. With the ultimate intelligent techluxury brand positioning, Faraday Future's first flagship product FF 91 Futurist is equipped with exceptional product power. It is not just a high-performance EV, an all-ability car, and an ultimate robotic vehicle, but also the third internet living space. ■

Volvo Cars Tech Fund Invests in Optical and Imaging Technology Start-up Spectralics

Volvo Cars has invested in the optical and imaging technology start-up Spectralics through the Volvo Cars Tech Fund, the company's venture capital investment arm. The investment gives Volvo Cars access to promising technology at an early stage of development that could contribute to making cars safer and revolutionise in-car user experience.

Coming from a background in aerospace technology development, Israel-based Spectralics creates state-of-the-art imaging and optical infrastructure spanning materials, hardware and software, enabling a wide variety of advanced optical capabilities.

One of the company's core solutions is the multi-layered thin combiner (MLTC) which is a new type of thin optics 'film' applicable to see-through surfaces of all shapes and sizes. Integrated into a car's windshield or windows, the technology could be used to overlay imagery on the glass.

In a windshield configuration, the technology could create a wide field of view 'heads-up display' that can instill a sense of distance as virtual objects are superimposed onto the real-world environment for a safe and immersive experience.

"Spectralics is an exciting company with technology that holds truly great promise," said Henrik Green, chief product officer at Volvo Cars. "By supporting their development, we can bring forward the potential their products could have in future Volvo cars."

Other potential uses of the technology include advanced filters for various applications, in-cabin sensing, blind-proof front-looking cameras and digital holographic projections.

"We are proud to partner with a progressive technology leader like Volvo Cars," said Ran Bar-Yosef, co-founder and chief executive officer of Spectralics. "We identify multiple touch-points with Volvo Cars' vision in the ecosystem and recognise future Volvos as the right fit for new technologies."

Spectralics is an alumnus of the MobilityXLab programme in Gothenburg, Sweden and is part of the DRIVE network in Tel-Aviv, Israel. They are both accelerators for promising start-ups with ideas that can break new ground in the mobility sector. Volvo Cars has been a leading partner in both initiatives since 2017.

"This investment is another result of our successful collaboration with MobilityXlab and DRIVE, and it deepens our relationship with these innovation partners," said Lee Ma, head of the Volvo Cars Tech Fund. "Spectralics is a good portfolio fit for us and we believe that their technology has the potential to set a standard for the next generation of displays and cameras."

The Volvo Cars Tech Fund was launched in 2018 and invests in high-potential technology start-ups around the globe. It focuses its investments on strategic technology trends transforming the auto industry, such as artificial intelligence, electrification and autonomous driving. ■

US Army to Expand Deployment of LiFi as pureLiFi is Awarded Another Big Deal

Global leader in LiFi technology, pureLiFi has secured another multi-million-dollar deal to supply the US Army with thousands of additional units of the LiFi Defence system, Kitefin™.

"The Kitefin™ system is now officially disrupting the ecosystem of wireless defence technologies. Kitefin provides the latest advancements protecting mission critical communications and has the potential to save missions and lives. We won't stop here; the train has now left the station and LiFi is on its way to even broader deployments and new markets. We will put LiFi in the hands of millions of users," says Alistair Banham, CEO of pureLiFi.

Technologies such as WiFi, 4G and 5G use radio frequencies to transmit data, which produce large areas of radio frequency emissions that are easy to detect, intercept, and can cause overcrowding resulting in slow speeds and unreliable communications due to increased RF congestion. LiFi uses light rather than radio frequencies resulting in wireless communications that is more reliable, significantly more secure, and simpler to deploy.

The US Army Europe is expanding their use of this cutting-edge technology as LiFi has proven to be reliable for the most critical communications. LiFi not only enhances the US Army's wireless connectivity toolset, but has demonstrated in action, that LiFi solves real problems faced by defence and national security.

"LiFi offer an extremely survivable form of communications."

ANDREW FOREMAN

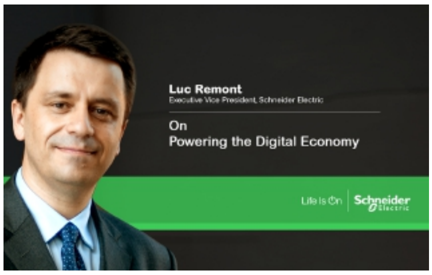
"LiFi technologies answer all three of the serious issues associated with the RF portion of the spectrum. First, due to the low probability of detection, jamming, and intrusion, FSO and LiFi offer an extremely survivable form of communications when in direct conflict with a near-peer adversary," said CW5 Andrew Foreman, USAREUR-AF Chief Technology Officer.

pureLiFi are recognised rising stars in the global technology scene and named one of the "EE Times Silicon 100 start-ups to watch" two years running. Having now secured multiple million-dollar deals with the US Army Europe, pureLiFi have officially made their mark on the wireless communications marketplace.

With growing demand for bandwidth hungry technologies, such as augmented and virtual reality, next generation manufacturing and the metaverse, new wireless communications technologies are needed to enable new use cases and technology breakthroughs.

pureLiFi is now offering high-speed components ready for integration into consumer electronics such as mobile phones, laptops and tablets, with a view of taking LiFi mainstream and offering unprecedented bandwidth, ultra-fast speeds and military grade security to the consumer. ■

GREENext Provides Sustainable and Resilient Energy-as-a-Service



Schneider Electric recognized as the World's most sustainable corporation in 2021 by Corporate Knights, and Temasek announced the launch of GREENext, a joint venture that will provide sustainable and resilient energy solutions to commercial and industrial customers through solar and battery hybrid microgrid technology. GREENext will utilise pre-engineered standardised microgrid technology, which increases deployment speed, that will distribute solar power and come with integrated, digitally optimised batteries to store power, providing an additional layer of reliability. As an Energy-as-a-Service, GREENext will remove the need for large upfront capital or expensive infrastructure upgrades throughout the lifetime of the contract. Powered by renewable energy, it will allow customers to reduce their carbon emissions, benefit from lower electricity costs and enjoy a more resilient energy supply.

This pilot phase will focus initially on India, with potential for further expansion to Southeast Asia.

Luc Remont, Executive Vice President, International Operations, Schneider Electric said, "Schneider Electric and Temasek share a vision of scaling technologies and businesses that can help the world transition to renewable energy. We are excited about how this venture can accelerate the renewable energy transition by removing the upfront capital barrier."

Nagi Hamiyeh, Joint Head of Investment Group and Head of Portfolio Development, Temasek said, "Enabling businesses to accelerate their decarbonisation efforts will be key to tackling the climate crisis we all face. Temasek has been actively investing in climate-aligned opportunities, catalysing breakthrough technologies and nature-based solutions that aim to usher in a low carbon future. We are pleased to be partnering Schneider Electric to explore how we can scale microgrid solutions to reduce the operational carbon emissions of companies in India, with the possibility of introducing such technology to other regional countries." ■

CSA Group Opens New Lighting Center of Excellence in Irvine, California

CSA Group, a global leader in Testing, Inspection and Certification, has announced the opening of a new Lighting Center of Excellence in Irvine, California. The new, state-of-the-art facility will centralize and enhance CSA Group's lighting evaluation services, directly addressing a need by manufacturers looking for a more streamlined testing, inspection and certification process and faster turnaround times.

Through the new Lighting Center of Excellence, CSA Group will provide a comprehensive set of services including OSHA NRTL (Nationally Recognized Testing Laboratory) certification services; energy performance testing, including LM-79; photobiological testing; photometric testing, including horticultural; and acoustic testing, among others.

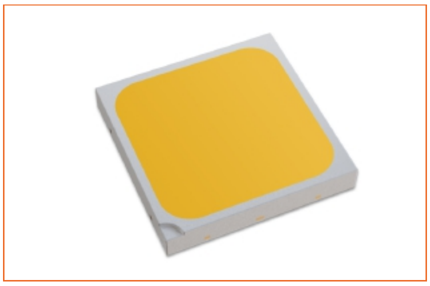
"Faced with an increasingly competitive marketplace and ongoing supply chain challenges, North American lighting manufacturers are looking for a testing, inspection and certification provider who not only helps them navigate the certification scheme requirements of products, but who understands their need to get products to market quickly," says KC Fletcher, Lighting Center of Excellence Manager. "Establishing our Lighting Center of Excellence in Southern California, in close proximity to many of our customers, will help us strengthen the customer experience."

CSA Group is at the forefront of advances in lighting testing, especially in the horticultural lighting industry. The new Lighting Center of Excellence will strengthen CSA Group's lighting evaluation capabilities for markets across the globe including certification services for Canada and Europe. The new Lighting Center of Excellence is accredited and recognized to test and certify to various local and international standards.

Visit CSA Group's Lighting Center of Excellence website to learn more. ■

TECHNOLOGY NEWS

LUXEON 5050 HE Delivers Higher Efficacy in a High-power LED



Lumileds, innovator of the original 5050 LED, has expanded its range of options to meet manufacturers' needs for differentiated solutions addressing cost, efficacy, and power. The new LUXEON 5050 HE LED directly addresses the increasing demand for solar and off-grid solutions, renewable power options, and improved sustainability metrics. It expands options along the efficacy–output continuum giving luminaire manufacturers the ability to better target performance to their customers' requirements.

"Driving ever higher efficacy levels supports sustainability objectives and it reduces payback cycles," said Mei Yi Product Line Manager at Lumileds. "The new LUXEON 5050 HE delivers 181 lumens per watt or more and allows for BOM cost reduction while maintaining the robustness and longevity expected from a LUXEON LED."

LUXEON 5050 HE delivers Lumileds industry-leading and superior flux maintenance and color stability in high sulphur environments and its footprint compatibility makes it easy to design into existing and new platforms. For outdoor, industrial, and horticulture applications where robustness, longevity, and efficacy are the driving attributes, LUXEON 5050 HE is the clear LED choice.

LUXEON 5050 HE is immediately available in 2700–6500 K CCTs at 70 CRI. It is characterized for both illumination and horticulture with lumen and efficacy ratings as well as PPF (µmol/s) and PPF/W (µmol/J).

Complete specifications and information for LUXEON 5050 HE can be found at `https://lumileds.com/LUXEON5050HE`.

All LUXEON 5050 LEDs are available for immediate sampling. Production orders are available now through our distribution network and lead times are up to 8 weeks. ■

Edison Opto UVA + White & UVC Series Customize Design Solution

Edison Opto offers customized UVA + White and UVC solutions for continuous disinfection to reduce bacteria and airborne viruses. In the wake of the global outbreak of COVID-19, the people's need for anti-epidemic, sterilization, and anti-virus products has escalated, ranging from portable sterilization equipment, home appliances sterilization, and public health sterilization.

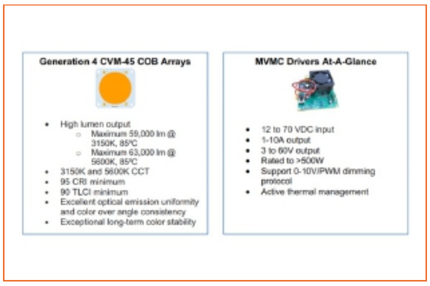
With the rise of environmental awareness and in response to the Minamata Convention, UV lamps containing mercury will need to be replaced by clean and more efficient LEDs. In the future, in the post-epidemic era, UVC LED products will continue to grow steadily in the sterilization, and purification, and water treatment markets.

To match this rising need, Edison Opto has launched new UV products and customized module services. UVC Mid-High power modules are ideal for portable sterilization devices, disinfection light tubes, disinfection panel light, etc. UVC High power devices are perfect solutions for disinfecting air, water, and surfaces. Furthermore, Edison Opto designed and manufactures UVA + White modules for situations that require continuous disinfection, such as hospital rooms.

In addition to providing complete each different application requirement, Edison offers customized services. They are matched with the different field requirements to achieve the best sterilization effect. The third-party unit test report shows that the sterilization effect can be as high as 99.99% in applying air sterilization.

About Edison Opto
Edison Opto from New Taipei, Taiwan, was built in 2001. The company's mission is to provide customers with a complete LED lighting product line. The line ranges from components, AC/DC modules, light strips, streets/outdoor lighting, after automotive lighting, and horticulture lighting. We established the integrated lighting design manufacturing service, LDMS helps customers manage every issue while designing LED lighting products.
`https://www.edison-opto.com.tw/en.` ■

Full Solution for Film, Stage and TV Studio Lighting



Luminus Devices is excited to introduce the CVM-45 COB arrays, specifically designed for studio and stage lighting, the first in a family of Robusto™ products. This new line from Luminus is able to deliver incredible 90% lumen maintenance and color stability beyond 36k hours, even at case temperatures as high as 120 °C.

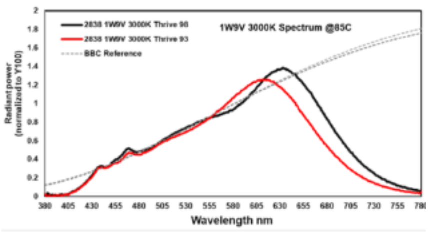
The first of the Robusto products, the CVM-45 COBs have outstanding color quality, high lumen intensity, and the industry's best flux and color stability over their operating life. The CVM-45, at 400 W to 600 W, delivers up to two times the flux levels of conventional metal halide sources, due to its high lumen output and directional emission – no more "replacement bulbs" needed. Over 50,000 lumen output is achievable at 5600 K and 500 W, with >95 TLCI and CRI, and >20k hours lumen maintenance. David Davito, COB Product Line Director, Illumination at Luminus, shares his enthusiasm for this new product line, "Combining outstanding color quality, 50,000 lumens of intensity, and the industry's most stable flux and color, the CVM-45 gives the film and TV industry the high output light source they can rely on for any project."

In an effort to streamline the design process, customers can pair the CVM-45 COBs with the Cuvée Systems recently released MVMC driver to create a full solution. The MVMC Series of LED drivers has been designed for mid-voltage, mid-current applications that are common to entertainment, industrial, and general lighting solutions. Supporting outputs of up to 10 Amps and 60V, the >500 Watt rated drivers offer excellent dimming flicker-free performance, and active thermal management to monitor LED temperature, current, and voltage. Kin Chan, Director of Product Management explains, "Our MVMC drivers can drive high voltage, high power LED arrays with precise deep dimming and flicker free which is needed for excellent high definition filming."

For a full list of features, applications and benefits of the CVM-45 COB arrays visit https://download.luminus.com/datasheets/Luminus_CVM-45_Datasheet.pdf. For a full list of features, applications and benefits of the MVMC driver visit http://cuveesystems.com/wp-content/uploads/2021/08/Cuvee_MVMC_Driver_DS.pdf.

As with other compatible Luminus COB and Cuvée LED driver combinations, the solution comes with a combined 5-year system warranty that covers both the LED and the driver. Both product lines are available through Luminus' authorized distributors. ■

Bridgelux Releases Thrive 93



Bridgelux Thrive is expanding its range of high-fidelity products to include both Thrive 93 and Thrive 98 (CRI of 93 and 98 respectfully.) Both families create a stable of LED solutions that represent the closest match to natural light across the critical wavelength range (from blue to green) for human health. Both Thrive products engage a broad-blue chip technology and a special phosphor blend to fill in the common cyan gap that plagues most LED solutions.

"The Broad Blue emission is what allows the Thrive family of products to match natural light so well," says Mark van den Berg, VP of Sales at Bridgelux. "By creating multiple blue emission peaks, we are able to better replicate natural light than competitors whose LEDs emit a single, narrow spike of blue." Benefits of the enriched blue spectrum and full spectrum coverage include improved eye comfort, sleep/wake cycle and emotional well-being.

Where Thrive 98 uses a longer wavelength red, which helps achieve R9 >90, Thrive 93's red peak is slightly shorter in the visible spectrum, which produces R9 >50. This slight modification creates a 12% competitive edge in efficacy over Thrive 98 and competing 90 CRI products. "In Thrive 93, designers can enjoy premium fidelity across the entire spectrum in addition to amazing efficiency all in the same LED package." says Tim Lester, CEO of Bridgelux.

Bridgelux in preparing Thrive 93 for the lighting design community created an extensive formal survey conducted with some of the top specifiers in Europe and North America. In over 30 hours of interviews, Thrive was compared to traditional 90 CRI products. Over 90% of those interviewed preferred Thrive to 90 CRI. Designers felt that colors rendered under Thrive were more natural. Surprisingly, designers also felt that Thrive was so successful at color temperatures that they wouldn't naturally use (such as 4000 K,) that they would consider expanding their palette to include a broader range of CCTs. Thrive products are being used across multiple platforms which ensures that you can bring sun-like quality of light to both your home and your office. ■

Enriched Light with Daylight-like Spectrum Improves Learning and Memory Function

Seoul Semiconductor Co. announced that following Seoul National University in Korea and Basel University in Europe, a research team found that exposure to short-wavelength enriched light with daylight-like spectrum improves key components of learning such as working memory, cognitive processing speed, and testing accuracy.

The clinical trial began in 2019, conducted by the Division of Sleep and Circadian Disorders at Brigham and Women's Hospital, a teaching affiliate of Harvard Medical School, and included college-aged adults. The results from the study clearly showed the effectiveness of improving procedural learning.

Shadab Rahman, PhD MPH, a researcher in the Division of Sleep and Circadian Disorders at Brigham and Women's Hospital and Assistant Professor of Medicine at Harvard Medical School, led the study along with Leilah Grant, PhD, Melissa St. Hilaire, PhD, Steven Lockley, PhD, and other researchers at the Brigham. Dr. Rahman said, "Even if the color temperature and brightness are the same, light with different spectra may affect non-visual responses to light exposure, including those of circadian rhythms and cognition, differently. In this experiment, we found improvement in working memory, cognitive processing speed, procedural learning, and testing accuracy with young adults under daylight-like light spectrum lighting compared to conventional-LED spectrum lighting. This is an important result that can inform lighting choices for indoor use to enhance students' learning and memory function."

The daylight-like spectrum lighting used in the study was provided by Seoul Semiconductor Co., Ltd., makers of SunLike. SunLike is an optical semiconductor technology that reproduces the natural sunlight spectrum curve, that is, the intensity of light for each wavelength of red, orange, yellow, green, blue, and purple. This new concept of LED light source embodies almost the same characteristics of natural light and is optimized for human 24-hour circadian rhythm accordingly.

There has been an increase in research activity on the relationship between light and human bio-function, including a recent scientific study focusing on the effects of light spectrum on sleep quality, visual comfort, well-being and daytime alertness conducted by Prof. Christian Cajochen and his team at the University of Basel in Switzerland, entitled: 'Effect of Daylight LED on Visual Comfort, Melatonin, Mood, Waking Performance, and Sleep,' published in the Journal of Lighting and Research Technology on March 24, 2019. In addition, in an experiment at Seoul National University College of Medicine in July 2018, it was demonstrated that vitality and alertness were increased when SunLike LED lighting was used.

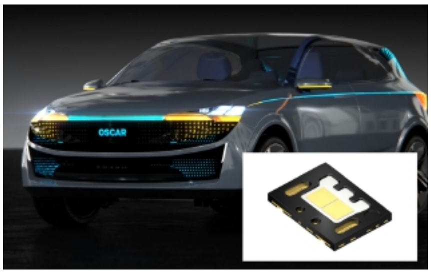
"As the saying goes, 'Mother Nature is great', the human body has a 24-hour circadian clock that has evolved to set its time by tracking the daily cycle of sunlight. SunLike is a technology that reproduces all wavelengths of visible light as closely as possible to sunlight. We've been working on R&D over the past 30 years to optimize this technology to provide plants, animals and humans access to light that is closest to sunlight to promote healthy circadian rhythms and sleep, which can also help children and students to study effectively and maintain good health", said Chung-hoon Lee, CEO of Seoul Semiconductor.

Seoul Semiconductor and Toshiba Materials were jointly involved in the development and release of SunLike in 2017, which has needed investment to further expand stable production and sales. As a result of continuous consultations between the two companies over the past two years to improve the speed of decision and operational efficiency for the SunLike business, Seoul Semiconductor has acquired all technologies, patents, trademarks, etc. related to SunLike, the light most similar to sunlight. Key workers from Toshiba Materials also joined Seoul Semiconductor, and they began efforts to expand sales from September. ■

New Oslon Black Flat X Family for Automotive Front Lighting

Automotive lighting has become extremely versatile thanks to new technological advances. In particular, further developments in LED technology have opened up new possibilities. LEDs require minimum installation space while impressing with outstanding brightness values, giving manufactur- ers enormous freedom in designing their lighting solutions.

"The Oslon Black Flat product family has been an ideal solution for high-quality and at the same time cost-optimized headlamp designs for many years,' said Philipp Puchinger, Marketing Manager Automotive Exterior at ams OSRAM. "With the two new products in the Oslon Black Flat X line, ams OSRAM is once again underlining its innovation leadership in automotive lighting."



The surface-mountable components can be processed particularly easily in manufacturers' stand- ardized production processes. In addition to the market-leading brightness of typ. 460 lm at 1 A, the 1-chip variant is characterized by its compact dimensions of 3.75 mm×3.75 mm. The special QFN platform of the LEDs enables customers to perform particularly simple thermal management. De- pending on the system, heat sinks can be significantly reduced in size or even eliminated alto- gether. The Oslon Black Flat X family's leadframe package also achieves a lower thermal re- sistance (Rth) than the leading ceramic packages in this context to date. Together with a special TiO_2 encapsulation, the black package of the LEDs delivers high contrasts of 1:200. In addition, the new components are characterized by a very homogenic color over angle radiation.

The Oslon Black Flat X family will start with a 1- and a 2-chip version. Various multi-chip versions will be added in mid-2022. ■

Infrared Laser Diode for Industrial LiDAR Applications

LiDAR, short for "Light Detection and Ranging," is one of the central technologies for autonomous driving. But there are also numerous applications for the three-dimensional detection of surroundings outside of the automotive industry. ams OSRAM, a leader in the development and production of infrared pulse lasers for LiDAR systems, is now launching the SPL TL90AT03, which is ideal for applications such as industrial automation, site leveling and invisible traffic monitoring.

"Our many years of experience in the development of infrared lasers and close cooperation with leading companies in the LiDAR field have given us a unique position in the market."

MATTHIAS HOENIG, MARKETING MANAGER FOR LIDAR AT AMS OSRAM

No matter which LiDAR application is used, the functionality of these systems is always very similar. A light source emits infrared light into the environment. When the light hits an object, it is reflected by the object and registered by a detector. Based on the time it takes the light to reach the object and back to the detector, the distance or structure of the object can be determined.

The SPL TL90AT03 from ams OSRAM was specifically developed for short laser pulses between 5 and 100 nanoseconds. The laser achieves an optical output of 65 watts from an aperture of 110 µm at a forward current of 20 A – corresponding to an outstanding efficiency of about 34 percent. The device comes in the proven and extremely rugged TO56 MetalCan package. The infrared component emits light in the established wavelength of 905 nanometers for LiDAR applications and is also suitable for a range of other applications thanks to its compact dimensions.

Another advantage of the laser is the particularly narrow emission width (the area in which the light leaves the component). It allows the use of compact optics and thus reduces the overall size of the system. In addition, the laser is available in another pin configuration as the SPL UL90AT03.

For more information on industrial LiDAR, please visit the website: https://www.osram.com/os/applications/industrial_lidar.jsp. ■

CES LIGHTING INNOVATIONS

Smart Multi-Color A19 Bulb with Health Monitoring Radar

Sengled is taking the smart light bulb where it truly has never been before with built-in health monitoring radar technology. Benefits include sleep tracking as well as certain biometric measurements such as heart rate, body temperature, and other vital signs. Frequency-Modulated Continuous Wave (FMCW) radar is used together with Sengled advanced proprietary AI algorithms to help users monitor health statistics. Multiple bulbs connected via a Bluetooth Mesh network work together to create a virtual map that can help detect human behavior and determine if someone has fallen and send for help. With it's Wi-Fi-Bluetooth Mesh dual-chip, no hub is needed. https://us.sengled.com/ ■

LED Color Bulb with Subscription Service

Abode used CES to mark the launch of its first color LED bulbs. The standout feature with these is a subscription service that gives access to a range of advanced automation features. That way. you can set multiple layers of conditions for the lights to be activated, set blackout periods, and tie in with other Abode smart home products.
https://goabode.com/ ■

Cync App, powered by Savant

The Cync App, powered by Savant, is a proprietary new mobile app for iOS and Android that controls GE Lighting, a Savant company's growing Cync family of smart home products sold at major US retailers and provides a custom, easy to use and convenient smart home experience.
https://www.gelighting.com/cync-smart-home-app ■

Carewear Light Therapy with Digital Health Ecosystem

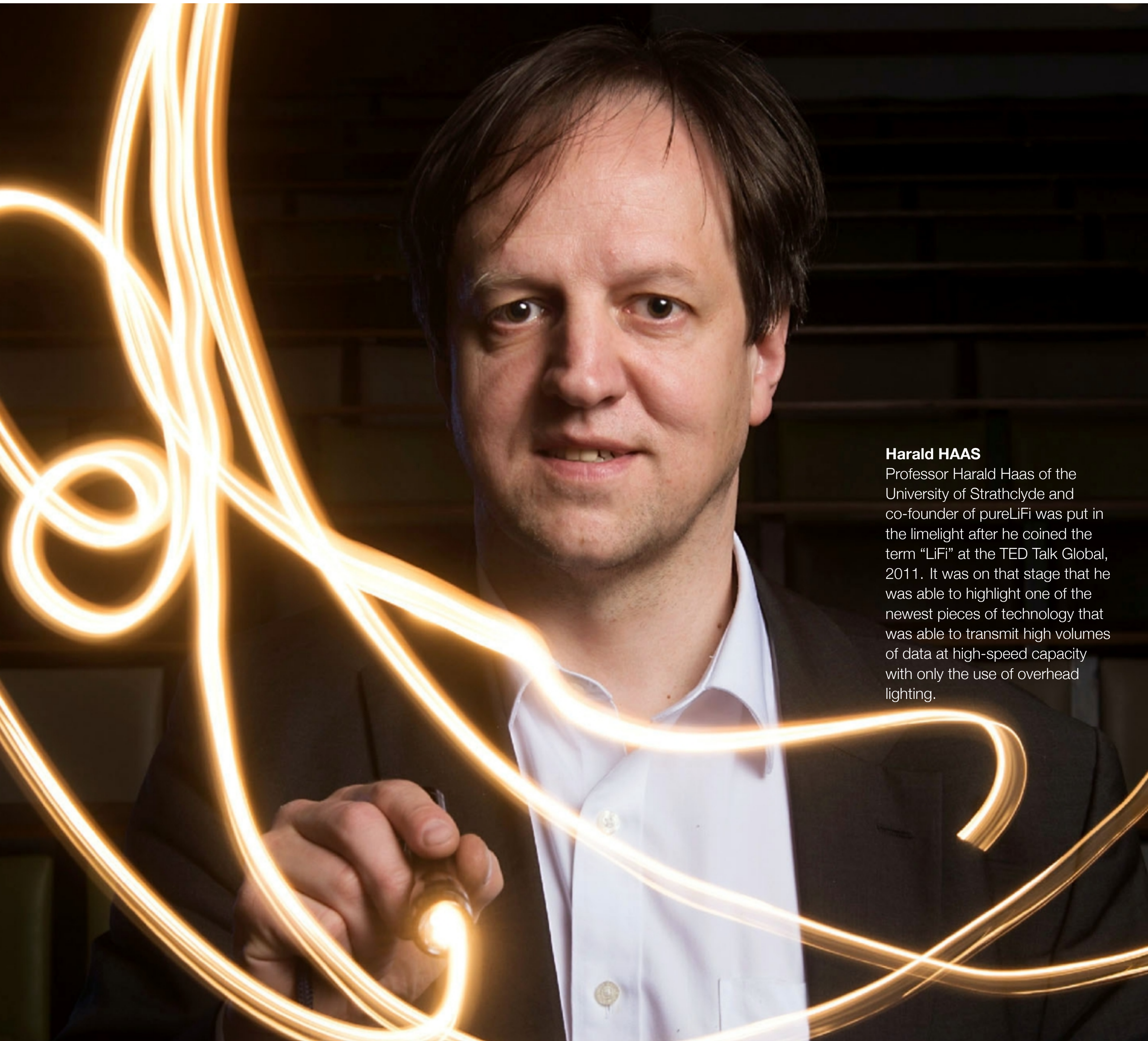
Carewear's Light Therapy system is a wireless, wearable, over-the-counter FDA cleared, CE MDD class IIa medical device for the management of pain, treatment of soft tissue injury, wrinkles and acne. It is paired with a digital health infrastructure allowing clinicians to select treatment parameters and outcome indicators, monitor utilization and report real-time through the cloud.
https://www.carewear.net/ ■

EVENTS

Light + Building 2022

As the pandemic situation continues to develop very dynamically, Messe Frankfurt is postponing the world's leading trade fair for light and building technology to autumn 2022. Last December, intensive discussions with customers and cooperation partners had already led to the examination of alternatives to the original date in March. Now the new date has been set: Light + Building Autumn Edition will be held in **Frankfurt am Main from 2 to 6 October 2022**. ■

"With LiFi, We See a Shift From a Device to a Platform in Lighting" Professor Harald HAAS, University of Strathclyde



Harald HAAS
Professor Harald Haas of the University of Strathclyde and co-founder of pureLiFi was put in the limelight after he coined the term "LiFi" at the TED Talk Global, 2011. It was on that stage that he was able to highlight one of the newest pieces of technology that was able to transmit high volumes of data at high-speed capacity with only the use of overhead lighting.

Recently, Professor Harald HAAS received the LpS Digital Award for the best scientific conference contribution. Dr. Günther Sejkora and Siegfried Luger had the honor of talking to Professor HAAS, founder of the modern LiFi technology. State of the art technology, applications, and realized projects were simultaneously fascinating and astounding. It was a lesson on how important it is to connect communication with lighting areas; a challenge and an excellent opportunity to utilize LiFi technology. Ten years after Professor HAAS' sensational TED Talk, the time has come for implementation. We want to encourage all lighting system developers to tackle LiFi effectively and exploit the potentials of LiFi technology.

LED professional: **Professor Haas, it's an honor for us to have you here for this interview. We are especially interested in interviewing you because of the LpS Digital online award you received for the best lecture in 2021. If you don't mind, could we start with some information pertaining to your history – both personal and in the area of research? How did a German engineer become a professor in Scotland?**

Professor Harald HAAS: First of all, please let me take this opportunity to thank Luger Research for the great honor of bestowing the Best Scientific Talk award on me! It was a humbling experience. So thank you very much.

You are right – I am a German engineer. I have a relatively long history in the industry. My career started with a scholarship from the Heinz Nixdorf Foundation, which enabled me to spend one year in Bombay as part of a team of Siemens engineers that was building a GSM network for the city of Bombay (now Mumbai). That scholarship took me out of a small Bavarian village and gave me my first international experiences. This practical experience got me very excited about mobile communications, and I wanted to learn more about the handset technology. Therefore, I subsequently started to work at Siemens Semiconductors in 1995, which later became Infineon. There, I worked with a team on a mobile communications chipset, which at that time was for the 2nd generation cellular technology, GSM. It was a chipset designed for the Siemens mobile division. In those days, we still had mobile phones from Siemens. So that was my first real experience in the mobile communications industry. I realized that there was still a lot to be discovered, and therefore I decided to work towards a PhD degree. My Heinz- Nixdorf scholarship inspired me to further my career in an English speaking country. In order to combine English and my PhD ambition, I reached out to the University of Edinburgh and they offered me a research post to pursue a PhD degree. While working on my PhD I worked on new technologies for the third generation of mobile networks, called UMTS, and I developed a patent. That patent was of interest to Siemens in Munich and the university sold the patent to the Mobile Communications Networks Division of Siemens. Siemens then offered me a research project manager position for a research project that included three Chinese and three German universities. I finished my PhD at Edinburgh University in 2001 and that same year started at Siemens. In the research project we created a significant patent portfolio for what would become the 4th generation of cellular communications, LTE. I worked on that very exciting project, but again, I came to the point of saturation and I wanted to step up and do more.

I then got an offer for a professorship at a new university in Bremen – the International University Bremen which later became Jacobs University. The freedom of academia was the motivating driver for my decision to move into academia. I was intrigued by the potential of 'mobile multimedia' and opportunities stemming from this paradigm shift. To calibrate with what was commercially available at this time, I need to stress that this was before the smartphone era. I realized at that time that the radio spectrum is a limited source and that was why I was intrigued by visible light communications. At around the same time the high brightness white LEDs started to get traction following the seminal work of Professor Shuji Nakamura and his colleagues on the development of the blue LED. White LEDs came out around 2002 or 2003 and we started to do some curiosity driven experiments at the university. That's why I started to combine visible light communication and lighting. I worked at Jacobs University until 2007 when I got an offer from the University of Edinburgh for an academic position there. And then I moved to Scotland with my family. So that's how I went from working in wireless engineering in Siemens to optical wireless in Scotland.

LED professional: **Scotland seems to be a focal point for LiFi research and development. Can you tell us a little about that and the role you play in it?**

Professor Harald HAAS: Yes, that's true. We seem to have a central activity in Scotland, but before I expand on that, let me say that the field of optical wireless communication has been around for at least forty years. And if you want to go back in history even further, you may even say that Alexander Graham Bell was the one that started that kind of research. As you may know, he invented the photophone before he invented the telephone. There is also a lot of work that was done in the 1980's by IBM research in Zurich around interconnections of computers. Stanford and Penn State University did a lot of work and many others. As you know, IRDA was a big topic in the 1990's, but it was all based on infrared. A colleague and collaborator, Professor Nakagawa, at Keio University was basically the main driver behind visible light communication around 1998 -2002. We were inspired by his work and drove it further in terms of data rates and towards a mobile wireless networking solution. Prof Nakagawa and his team primarily focused on point to point connectivity, an example of which is underwater diver-to-diver communication. The reason why this is a very interesting use case is because it is not possible to communicate over longer distances under water using radio frequency signals. They had a prototype of two flashlights being held by two divers to help them communicate under water. This was an exciting application, I must say, but our vision was to combine my experience in cellular communications with the opportunity to use light as a medium to build cellular networks. I believed and still do believe that the radio frequency spectrum crunch is the key differentiator from earlier attempts of introducing optical wireless networks. And that really drove us to adopt visible light communications and transform it into a full mobile wireless network solution. After five years of fundamental research, I started my translational research with exactly that vision by applying for a Scottish Enterprise funded project, D-Light, in 2008 when I moved to Edinburgh with the clear intention of creating a company, realizing that there was a lot of commercial value in that technology. The last required milestone of the D-Light project was the formation of a company.

It was clear from the start that we will commercialize the results of the D-Light project through a spin-out company, and the TED Talk Global invitation during the project came in very handy. The D-Light project ran between 2009 and 2011 and we founded pureLiFi in January 2012. We are now celebrating the 10th anniversary of pureLiFi. pureLiFi, I think, is one of the leading international companies selling LiFi products. You may have seen recently that there has been another big deal with the US Army Europe and Africa, who are buying these LiFi units by the thousands. So, the pilot phase has ended and we are in the full deployment phase of LiFi networks. My vision was to translate visible light communication into a wireless networking technology and I think we are there. And around the commercial activity I wanted to establish a very strong research center. That's why I established the LiFi Research and Development Center (LRDC) where we continue to do very fundamental work and translate it to high technology readiness level prototypes. With the prototypes we aim to address the full and broad LiFi market – from satellite comms to in-vivo wireless networks. I believe there is very strong and broad LiFi activity now in Scotland. We have pureLiFi for commercialization and we have the LRDC with a total amount of competitive won funding since 2013 of around £18 million driving the research. I'm really proud of the strong cluster we have developed here. I also want to say that there are a lot of excellent activities going on around the world such as in China, the USA, Canada, and Europe, and we maintain strong international collaborations around the world.

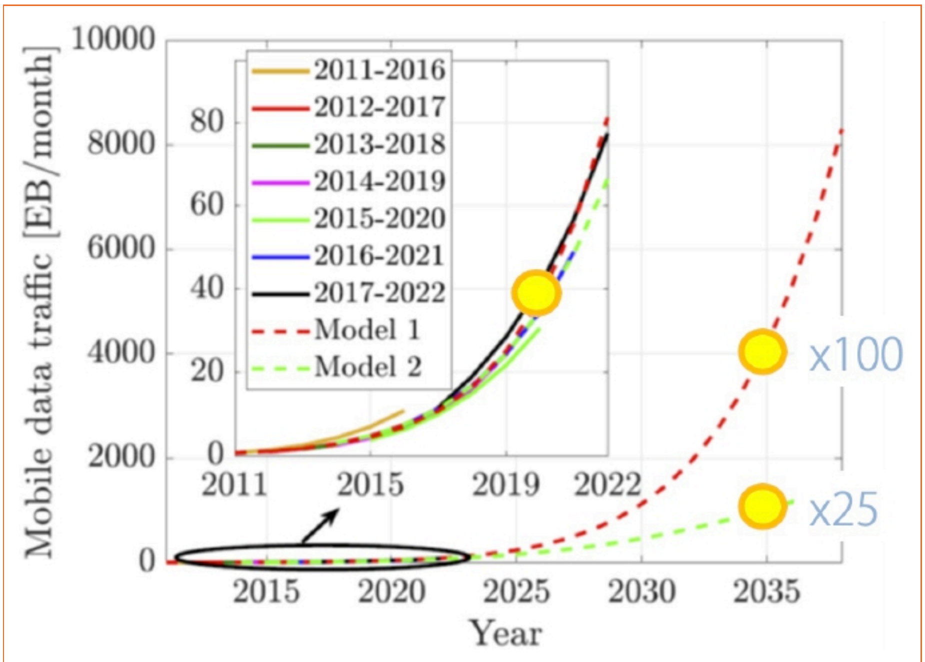


Figure 1: In 13 years, mobile data traffic will increase 25 to 100 times from today. Reference: T. Cogalan and H. Haas, "Why would 5G need optical wireless communications?," 2017 IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), Montreal, QC, 2017, pp. 1–6, doi: 10.1109/PIMRC.2017.8292749.

LED professional: How many people work in the research center in Scotland?

Professor Harald HAAS: The research center currently employs around 20 people. They are primarily research and development engineers, postdocs and PhD students and also academics. The LRDC is now at the University of Strathclyde, where we moved to in 2020. Here we maintain collaborations with major clusters around 5G and quantum technologies including the Fraunhofer UK and the Institute of Photonics led by Professor Dawson. Our research is structured into three horizontal layers: 1) Fundamental Devices (so fundamental transmitter/receiver devices), 2) subsystems and 3) complete wireless systems. Then we have a vertical structure which are applications ranging from 5G and now 6G, health, IoT, net-zero, security, and so on. So basically we translate our research into these applications. We engage with the industry, and we obviously have a link with pureLiFi, but we work with the industry as a whole – for example – we also work with SoraaLaser, now Kyocera SLD Laser (KSLD) and have driven their novel lighting devices to new heights in terms of data rates of white light.

LED professional: There are two different terms for light communication: one is VLC (Visible Light Communication) and the other is LiFi (Light Fidelity). Could you give us a short explanation of the difference between the two?

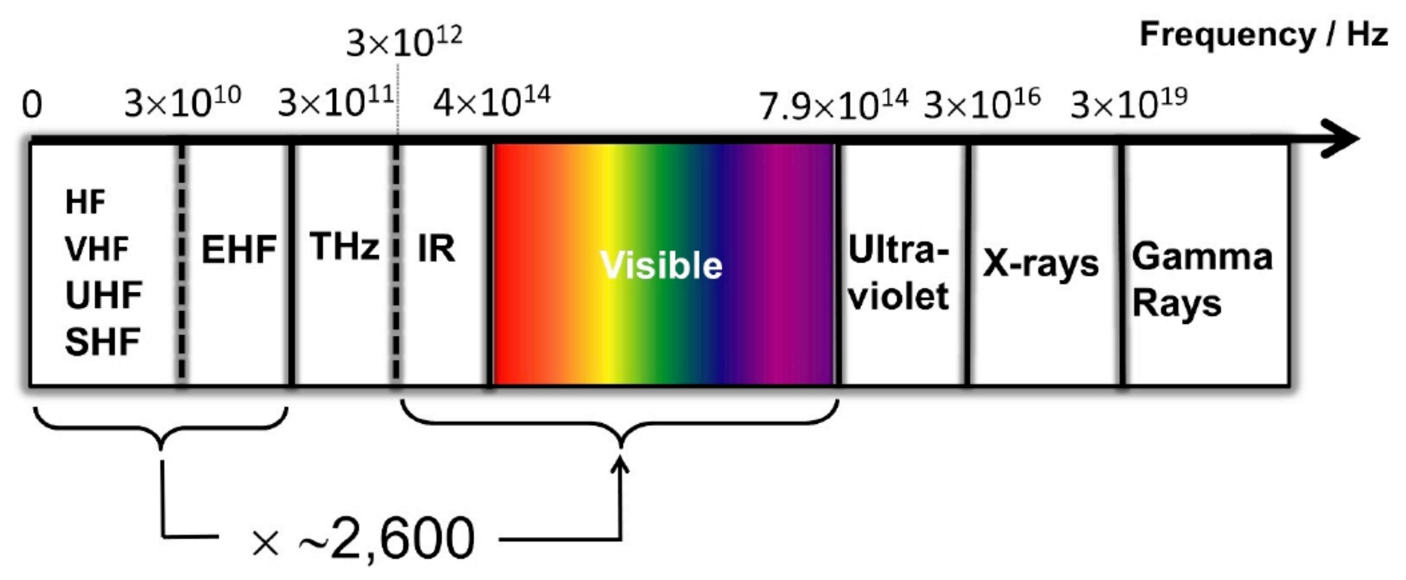


Figure 2: The combined visible light and infrared spectrum is 2,600 times larger than the radio spectrum. Reference: Haas, H., Elmirghani, J.; and Haas, H. 2020 Optical wireless communication, Phil. Trans. R. Soc. A.37820200051, http://doi.org/10.1098/rsta.2020.0051.

Professor Harald HAAS: That is a very important question. In short, visible light is using what the name says, using visible light for data communications. LiFi is wireless networking with light. And that is visible light and also infrared light. Essentially, LiFi uses the entire optical spectrum to build wireless networks. Visible light communications is an element of it – primarily the downlink element – this is the communication link from a fixed access point or base station to a mobile terminal. For creating an uplink, that is the link from the mobile terminal to the access point or base station, we use invisible light, for example, infrared light, because we do not necessarily want to shine light from our smartphone when we communicate bi-directionally to the access point. So basically, you have both technologies incorporated within the LiFi vision.

LED professional: So is it always the case that the downlink is through VLC and the uplink is through infrared?

Professor Harald HAAS: That is a concept, but having said that, it is also possible to use infrared for the downlink. Imagine if you want to communicate during the day: You probably do not want to have the lights on, so you could switch to an IR link. It's really using the entire optical spectrum to build a wireless network.

LED professional: We have known about visible light communication together with light fibers for ages. On the other hand, LiFi is a pretty new technology, or at least only recently becoming known. The roots go back about forty or fifty years. Can you tell us a little about the history of LiFi? When did it start to become so interesting?

Professor Harald HAAS: The history goes back as far as Alexander Graham Bell in 1880 with the photophone. It was a very ingenious development. What he did was, he used sunlight in conjunction with a transmitter that was a vibrating mirror that changed its angle. The change of the angle was in accordance with the voice captured by a microphone. So he got the intensity of a light beam modulated and sent this signal over a distance of 200 meters. On the other end he had a parabolic mirror and in the middle was a selenium cell, which is a detector, and the selenium cell caught the amplitude changes from the mirror. And then he had a speaker, where he decoded the direct modulated signal, into speech. So, he transmitted voice using sunlight over 200 meters and allegedly he was really excited about his invention. He even thought about naming his second daughter Photophone! He thought it was his biggest invention. But three years later he invented the telephone, which obviously became the device he is best known for.

This invention has laid the foundations of LiFi. In the 1950's we had the TV remote control which was free-space one-directional point-to-point communication using the infrared spectrum. As you say, fibercom came up. Fibercom is primarily infrared through the fibers, and that's the backbone of our modern communication networks. Charles Kuen Kao, who was the inventor and pioneer of fiber networks, really is the "godfather of broadband". In his seminal work light was confined and guided through a glass medium. And then in the 1980's IBM research did pioneering bi-directional optical wireless networking using infrared devices.

"We are currently involved in a research project called TOWS for 6G, looking at the wireless connectivity of a terabit per second. At the moment, 5G is, in the best case, one gigabit per second. So, this is a thousand times more, with light."

PROFESSOR HARALD HAAS

These wireless networks primarily were designed to communication static computers. This work then led to standardization activities through the Infrared Data Association (IrDA). Then we witnessed the high brightness white LED at the end of the 1990's. My colleagues and I realized the opportunity to use these devices for light communication. We want to use combined visible light and infrared spectrum, which is 2,600 times larger than the radio spectrum, to add gigabit and terabit per second capabilities to 6th generation cellular networks, in order to overcome the spectrum crunch and enabling all the business opportunities in the lighting industry – for them to become telecom providers as well as lighting providers.

LED professional: That brings me to our next topic: In your award-winning lecture you explained that one of the biggest advantages of LiFi is higher data volume you can transfer due to the bandwidth offered by optical radiation. Why is it necessary to increase our data volume by such a high number?

Professor Harald HAAS: I think that is a very important question and I need to say upfront that at the moment we are currently involved in a research project here in the UK, called TOWS (Terabit Optical Wireless System for 6G). You may refer to it as LiFi 2.0. So, we are really looking at the wireless connectivity of a terabit per second. So, this is 10 to the power of 12. At the moment, 5G is, in the best case, one gigabit per second. So, this is a thousand times more, with light, and in particular, in this case, with infrared light. The reason why we need it is, if you watch the industry, we just had a big shift in social networking, with Facebook rebranding into Meta. There may be non-technical reasons for this change but there are also technical reasons. It's a way of creating the cyber physical continuum. So, creating a metaverse where, in the future, you're not only experiencing a two dimensional screen in front of us, but a three dimensional experience with holographic displays or four dimensional experience where you also get sensing data through the optical system, and many more dimensions. So, you really would immerse into a virtual world as if you were in a real world. The cyber physical continuum which also includes 'digital twins' is something that is being driven in the industry at the moment.

"The cyber physical continuum which also includes 'digital twins' is something that is being driven in the industry at the moment."

PROFESSOR HARALD HAAS

I don't want to go into all the dimensions, but if we only pick two dimensional XR (extended reality) experience, where you want the same visual experience as in a real-world and do not want to get seasick, when you have an augmented reality or virtual reality glass in front of you, you've got to have the same resolution. This includes having the same vision, the same latency that you would have in a real world. To achieve this one would need data transmission speeds, without data compression, of around one terabit per second. Obviously, there is data compression happening, but you still need around five gigabits per second to have a very good experience with your AR VR glasses. That is one of the main drivers why you need really high data rates and the bandwidth of RF is limited.

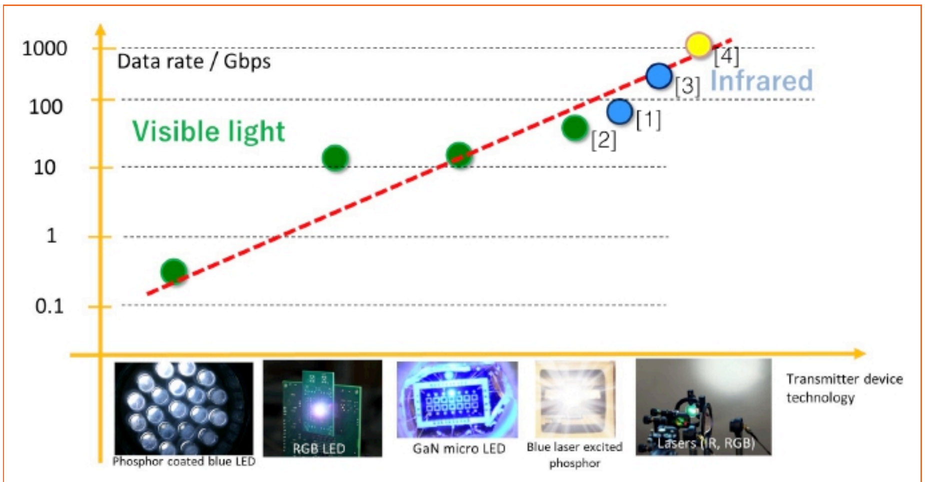


Figure 3: Available visible and infrared light technologies and devices. References: [1] D.Tsonev, et al., "Towards a 100 Gb/s visible light wireless access network," Opt. Express 23, 1627-1636 (2015). [2] T.Koonen, et al., "Ultra-high capacity indoor optical wireless communication using steered pencil beams," 2015 International Topical Meeting on Microwave Photonics (MWP, Paphos, 2015. [3] A.Gomez et al., "Design and Demonstration of a 400 Gb/s Indoor Optical Wireless Communication Link," in Journal of Lightwave Technology, vol. 34, no. 22, pp. 5332-5339, 15Nov.15,2016. [4] E. Sarbazi, et al., "A Tb/s Indoor Optical Wireless Access System Using VCSEL Arrays," 2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications, London, United Kingdom, 2020, pp. 1-6, doi: 10.1109/PIMRC48278.2020.9217158.

LED professional: Where is the limit of RF communication in the bandwidth?

Professor Harald HAAS: The limit is that the spectrum that is available in radio is 300 giga Hertz. That includes all your radio and TV broadcasts – all of the various wireless systems including satellite systems. And our prediction is, from these growing applications, that in ten years you will need at least 57 giga Hertz of additional bandwidth – this is roughly a fifth of the entire radio spectrum. It is unlikely that this level of new spectrum can be found in the RF domain. A solution would be to use of the tera Hertz spectrum between 300 giga Hertz and 10 tera Hertz, but devices that can operate in this spectrum are only currently being researched and developed. An additional challenge is the signal processing capability of current semiconductor devices which support maximum frequencies up to about 300 giga Hertz. However, as you alluded to, there are solid state lighting devices that can be used for free-space optical communication as well as devices used in fibre comms and together they can be used to build very high speed, high performing networks to really drive the future generation of wireless technology and services around it. In addition, since we apply intensity modulation and direct detection, the signal processing requirements are linked to the electrical bandwidth of the device and are, therefore, well within the capability of current semiconductor processes.

LED professional: So, volume is one of the big advantages of LiFi and I believe there are additional advantages, am I right?

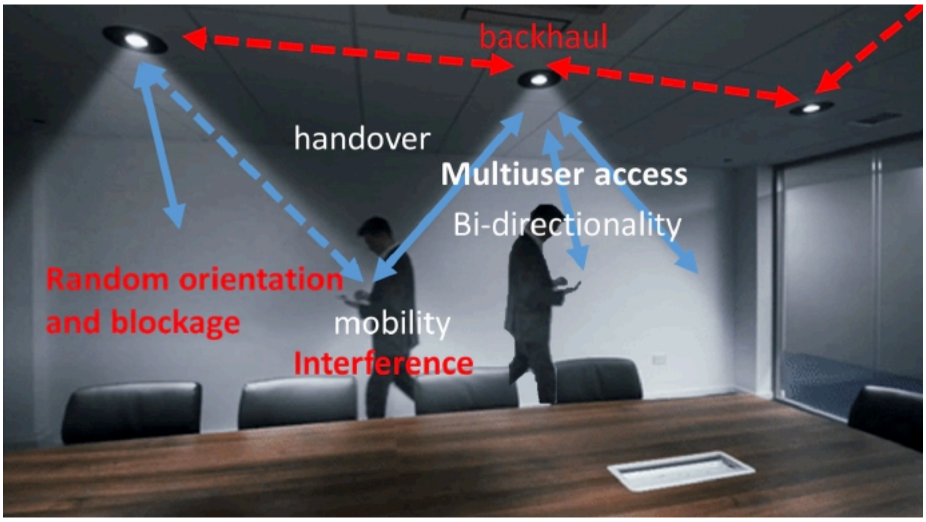


Figure 4: LiFi networking between light sources and mobile devices in rooms. A LiFi system will support user mobility and random mobile device orientations. In addition, a single LiFi access point, which is the downlighter, will connect multiple mobile terminals in a bi-directional fashion. If a single link is blocked, there will be other links that will provide backup connectivity. Every downlighter will cover a certain area and when users cross coverage areas the system will initiate a seamless handover to ensure continuous connectivity. There will be overlap regions where interference will occur which can be mitigated by joint transmission techniques. Lastly, every downlighter has a backhaul connection which connects it to the internet. This backhaul connection can be wired or wireless.

Professor Harald HAAS: An almost unlimited bandwidth is one of the key advantages. And the other main advantage is security. That's why pureLiFi, if you look at the news, has a strong engagement with the US Army Europe and Africa – who have coined the phrase: "Save Missions and Lives with LiFi."

The reason being: a WiFi router in an operational theater on the ground in a battlefield scenario can be easily detected outside the operational theatre as radio waves propagate through the fabric. It does not take a lot of sophisticated equipment to detect the radio equipment that poses a great vulnerability in that type of situation. But, LiFi inside the operational theatre has been proven not to create any digital signature outside it.

The same security features can be extended to an office environment to offer secure wireless communications in critical locations such as the CEO's office, boardrooms – essentially everywhere where eavesdropping may result in security vulnerabilities which extends to manufacturing sites. In the modern world, where cyber security is very important, LiFi has a very strong advantage. Moreover, it has the potential to be more energy efficient due to intentional wireless data links.

LED professional: How will the downlink through LiFi be realized in a lighting installation? Will the light coming from the luminaire be modulated or is it a separate channel? Why should we, let's say, modulate the LED driver output light, because then it would always have to be switched on.

Professor Harald HAAS: It's both – because the visible spectrum provides a vast amount of wireless transmission resources. Just to give you an example, we have taken red, green, blue and yellow LEDs off the shelf from Farnell. The entire set of SMD LEDs was less than a Euro. And we constructed a white light beam out of these four colors over 1.6 meters (the typical distance between a light in the ceiling and a smartphone in a walking scenario) and transmitted 15.7 gigabits per second. And that's 15 times faster than you have in 5G, so it's a viable spectrum to be used for wireless data transmission.

If you have a light and it's turned on and you're illuminating anyway, why not piggyback high-speed downlink data communication? It is more or less for free and it conserves energy because the light is on anyway. If I really want to take it forward to the next generation of illumination devices, it may be a discussion for the industry, but there are also people like Professor Nakamura and others that promote laser lighting. So really, the next wave of lighting is based on a blue laser instead of a blue LED. We've done a lot of experiments with laser lights and basically at CES 2020, demonstrated 20 giga bits per second with white light over a distance of three meters in a hotel room in Las Vegas, and 104 Gbps at CES 2022. And we're driving that data rate further so 104 giga bits per second from a light in a room is far beyond what any WiFi router can currently do. When the light is turned off infrared light can continue to provide wireless data. Moreover, the same devices can be used for sensing and the same optical system may be used as a Lidar system. There is a huge benefit in terms of multiple use cases using the light.

LED professional: Would that also mean that these lighting systems will always consist of RGB or infrared solutions but no phosphor LEDs because it has a delay? And what about white phosphor LEDs?

Professor Harald HAAS: The 20 giga bit per second with laser light was based on phosphor excited – not phosphor coated – illumination. A blue laser is shining on phosphor which creates white light, and this still allows gigabit per second data speeds because of the high bandwidth of the laser. Obviously, it is possible to use RGB. In fact, one would be better off using RGB. But if the white light comes from phosphor coated blue LEDs, it is still possible to get substantial data rates from it. In some IoT applications, you don't need a high data rate: you can serve a lot of sensors in a room using the phosphor coated LED.

LED professional: On the subject of micro LEDs: we have pixelated lighting with RGB, that would support LiFi quite well, wouldn't it?

Professor Harald HAAS: Absolutely. I've been working with my colleague, Professor Martin Dawson, for nine years now and we have pioneered the use of micro LEDs for wireless data communication. In 2014 we wrote a paper demonstrating three giga bit per second from a single blue GaN micro LED with an optical output power of five milliwatt. And now, we have them in displays. This offers the opportunity to transmit independent data streams from each pixel in a display. As a result it is possible to achieve massive parallel data streams

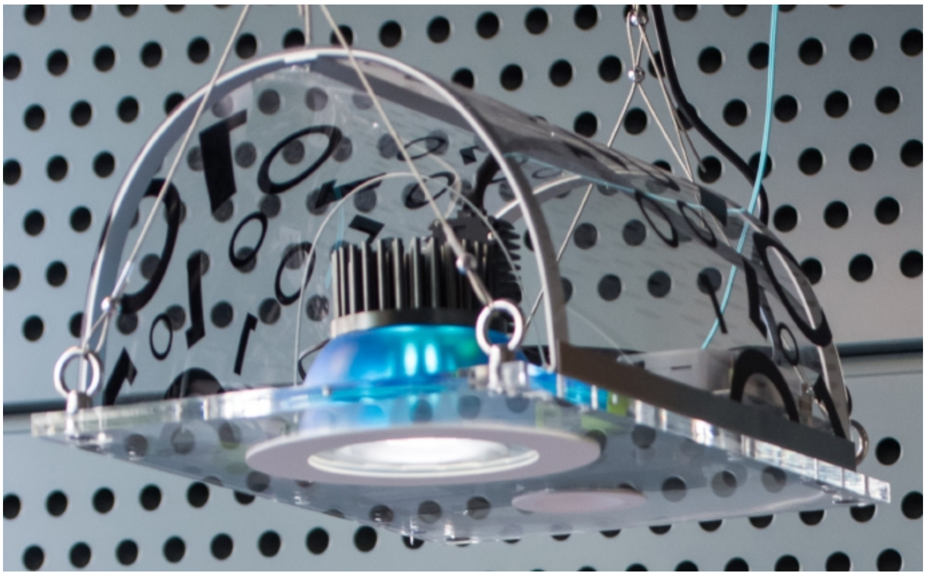


Figure 5: The figure shows a pureLiFi LiFi-XC access point. The actual data transmitter is an ordinary LED downlighter which is connect to a special driver that also provides high speed data channels to multiple users via the same light. This access point is also equipped with a light detector which can be seen next to the downlighter. This acts as a LiFi data receiver for the uplink connection.

via spatial multiplexing by means of MIMO (multiple input multiple output) and/or wavelength division multiplexing (WDM) So, it is possible to linearly increase data rates with micro LEDs. This is another great commercial avenue by enabling displays to be a massive MIMO transceiver.

LED professional: **In your lecture you made the example of the comms industry – from the device into the platform. You showed that the lighting can go from the device and into the platform using the example of a bulb with an intelligent micro controller inside. But what has to be done to achieve that? Where are we when it comes to platforms for light bulbs or lighting systems?**

Professor Harald HAAS: This is one of my favorite topics! First of all, the proposed concept drives the paradigm of edge computing that is discussed in cellular communications. In fact, it takes all the winning paradigms in cellular communication to new heights – cell densification, data rates, and latency. For example: for automation – if you think of a scenario within a manufacturing environment, where there are robots that need to react to certain stimulus within their operations very quickly, and there is the need to have very low latency between someone controlling the robot the wireless system must have very low end-to-end latency. In this case, it may not be possible to route the traffic through the world wide web and cloud servers located in Los Angeles, for example, when it is a factory located in Europe because the delays are tremendous. So, there is the need for having local communications and edge computing and local clouds close to the application. The lights could be exactly this – a communication device, a sensing device, a computing device, a data storage device and a cloud server. If you think of a shop floor environment where you manufacture things like an aircraft, and you have tools that are getting data from the cloud, based on the location of the tool, the system realizes what kind of screw or what kind of torque needs to be applied and it is automatically fed to the tool and it adjusts its action.

"In my view there is a strong commercial opportunity on the edge between communications and lighting."

PROFESSOR HARALD HAAS

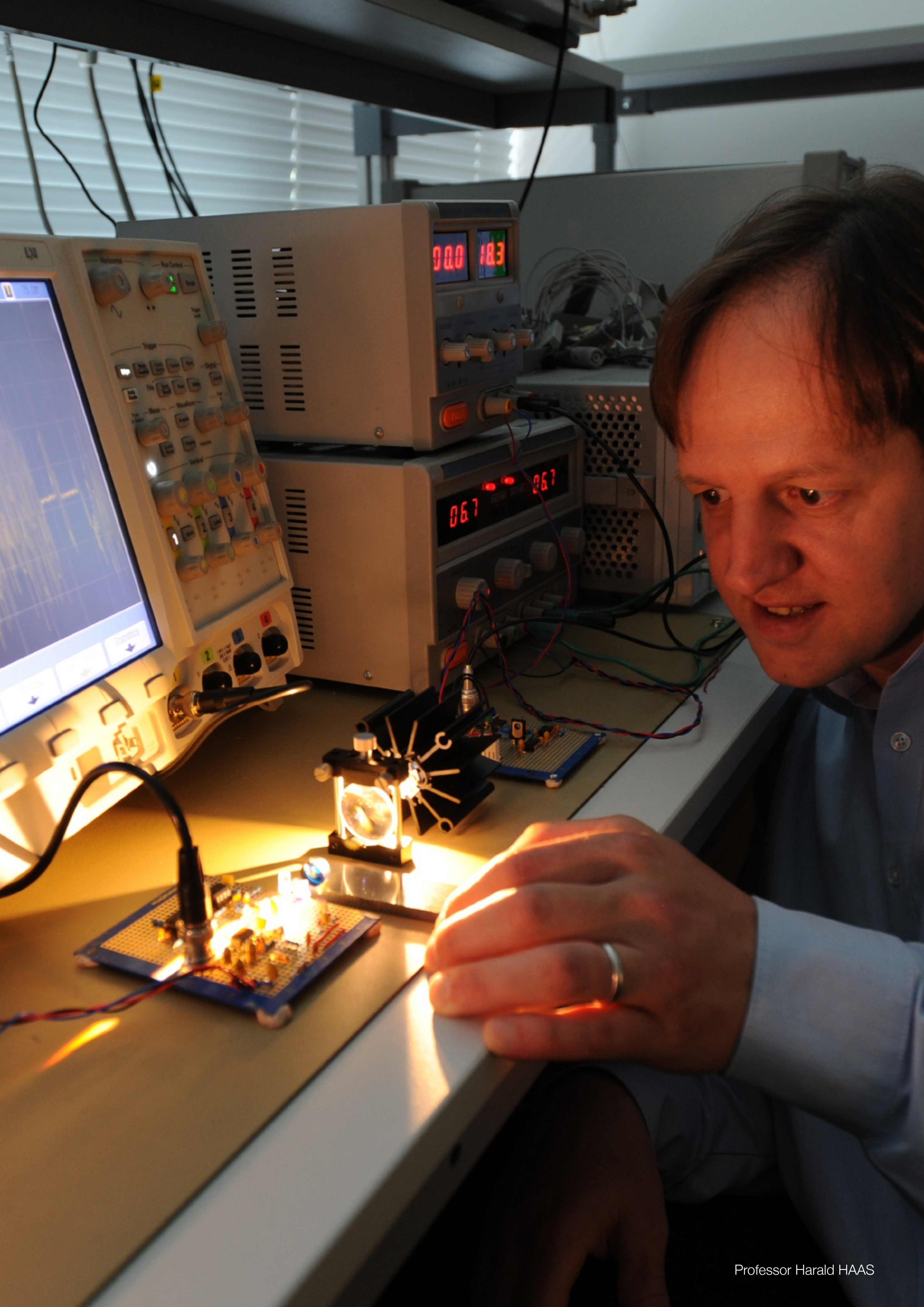
This type of scenario also requires low latency, high speed data communication and reliability. And again light bulbs could take this action – not only in a manufacturing environment but also in a home environment. And as I said in the lecture, like the mobile phone was a single-service device for mobile telephony at the beginning of the 1980's, the light bulb has been a single service device for lighting for many, many years – since Edison.

The mobile phone has developed into a mobile computing platform providing hundreds of services/apps. Similarly, we see a shift from a device to a platform in the lighting industry. A prerequisite for this is the service diversification. Illumination isn't something that is sustainable as a business model because of the lifetime of these devices. It's a necessity to add value to it, so now, we are taking the opportunity of moving a lighting device into a lighting platform.

This is enabled with all the components described above around communications, computing and sensing. If you wanted it to, a lightbulb could morph into a neuron of our future AI driven 'metaworld'. It could be a crucial enabler for ultra-smart buildings, smart homes, and smart cities. But there is also a challenge. This vision sits between two major industries: the lighting industry and the wireless comms industry. If you talk to the wireless comms industry – they don't want to hear about lighting. And if you talk to the lighting industry, they don't want to hear about communications – because that's not what they do. It's a real challenge bringing those two industries together, but I still hope I can convince them of the huge benefits. It can't be done in a radical way: you need small startups that realize the commercial potential to be had by this fusion of the two industries, and then they can drive the bigger industry and take the large corporations along that vision. In my view there is a strong commercial opportunity on the edge between comms and lighting.

LED professional: **If we talk about platforms, I think the next thoughts should be about standards. How far would you say we are in the field of standards, right now?**

Professor Harald HAAS: We are quite advanced with standards. And there is one standard that really stands out that encompasses the networking vision, and that is within IEEE. It's called IEEE 802.11 which is the body that standardized WiFi. And within this body of WiFi standardizations there is a task group



Professor Harald HAAS

called Task Group 'bb' that has defined a standard for LiFi. There is a first draft out there and we will see a ratified standard by the end of this year. So, in the first quarter or half of next year, you may see pre-standard products and by the second half of this year you'll see fully standardized products.

LED professional: You mentioned that pureLiFi has been given another award for the LiFi defense system Kitefin. You also made a multi-million-dollar deal with the US army. Could you explain to us what Kitefin is?

Professor Harald HAAS: The Kitefin is a LiFi system that is based on visible light for the downlink. It's a ruggedized wireless access point and lighting system that provides illumination and at the same time delivers secure and reliable bi-directional wireless data capacity. It's a most advanced visible light communication system for illumination and data communication and operating in harsh environments. It has near zero EM signature and saves time and money on deployment due to the simplicity of installation.

LED professional: What do you think the technological challenges are in the near future? And when do you think we'll be ready to have marketable LiFi solutions?

Professor Harald HAAS: I believe that the press release you just read is a marketable LiFi solution because it is important to note that these deployments are not proof-of-concept. They are not pilots. The US Army Europe and Africa are not piloting these devices for LiFi, they are rolling them out in real world deployments. So, that's the beachhead market. These are the first adopters, and we are very grateful to all the visionaries in the US Army who see the great benefits of LiFi.
But I guess you're talking about the consumer market. You're talking about deployment in our offices or homes. Maybe on our streets, streetlights, in our cars. We are on the brink of breaking into the mass market. One of the challenges is the integration into a small device. Bringing LiFi technology into a handset is the ultimate goal and everybody that is working on LiFi would, I suppose, declare this as an objective. So making it small – not bigger than the size of a camera module – is the objective. And I'd like to say here, that this is not fiction. Actually, pureLiFi released the first LiFi light antenna module small enough for integration into smartphones in 2019. This light antenna module is not bigger than a camera module, communicating gigabits per second via LiFi and doing use cases such as device to device communication.

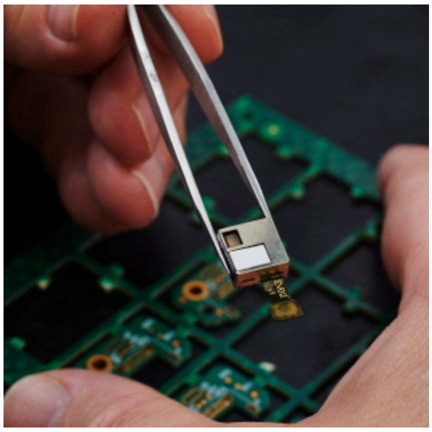


Figure 8: The figure shows the pureLiFi light antenna module (LAM) for integration into smartphones and lighting systems. First smartphones have been equipped and trialled with this LAM.

So it's not a research challenge, it's an engineering challenge that has already been solved. We are now waiting for it to come out in a real commercial mass market. But given the state of development, I don't see it taking longer than a year or two.

LED professional: You mentioned the communication business on the one side, and the luminaire business on the other side: So if a luminaire manufacturer thought to themself that it might be the right time to step into the LiFi business, how should they proceed?

Professor Harald HAAS: First of all, I think it would be great if a lighting manufacturer realized the commercial opportunities of combining lighting and communication. It would be a first step and I really want to highlight the very important developments in communications because one of the paradigm shifts in 5G is the move into the cloud. Radio access technologies – Open-RAN, for example, means that a lot of the processing of the communication signals is done in a cloud.
And a cloud is computing devices spread around or distributed – and the idea of computational centers – communication

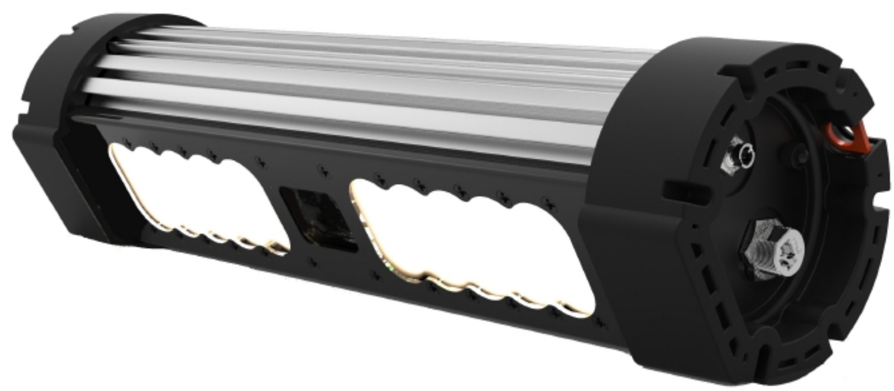


Figure 6: The Kitefin™ system by pureLiFi is already disrupting the ecosystem of wireless defence technologies. Kitefin provides the latest advancements protecting mission critical communications and has the potential to save missions and lives.

Figure 7: The LiFi-XC by pureLiFi is the world's first certified, complete LiFi system. The LiFi-XC system consists of an access point and USB dongle that is compatible with Windows, Linux, and MAC operating systems.

centers for radio comms, and so on – moving the cloud out into the edges; into the light bulbs, is a natural step. It is a natural step of the cloudification, as they call it, of cellular communications. But that trend has already started. So all a lighting company would need to do is to realize the opportunity and say – okay, we will suck the cloud into our light bulb, and have our "living room cloud" and our "kitchen cloud" – so having a cloud spread around in a house, storing local data in an environment; storing local information – having senses included as well, and filling an entire ecosystem of applications around it where lighting is one of them. Intelligent lighting – switching on and off or changing color depending on the moods of the people, would, at the same time, be providing services to them. I would imagine it would require a shift in skills in a lighting company.
A shift of skills where communications experts would need to be consulted.
And of course, a natural step for those companies would be for them to speak to people like us. They could hear from us and others what technologies exist to combine lighting and wireless communications and explore the opportunities.
There is a lot of advice that can be given in terms of what needs to be done.

"I really want to highlight the very important developments in communications because one of the paradigm shifts in 5G is the move into the cloud."

PROFESSOR HARALD HAAS

Likewise, there is a lot of advice that they could give to us, sitting on the communications side, in terms of the cost structure of lighting and the drivers in that industry. We could put things together and build a system that fulfils the requirements of lighting plus communications. It's really a matter of reaching out to people across that sector.

LED professional: Thank you so much! It has been an honor being able to talk to the founder of LiFi. We really appreciate all the time you have taken for us and our readers.

Professor Harald HAAS: Thank you as well – it has been an absolute pleasure! ■

About Professor Harald HAAS:
Professor Haas is a Fellow of the Royal Academy of Engineering, the Royal Society of Edinburgh, the Institute of Electrical and Electronics Engineers (IEEE) and the Institution of Engineering and Technology (IET). In 2017, he also received the Wolfson Research Merit Award of the Royal Society in the United Kingdom. This very prestigious Award aims at retaining respected scientists of outstanding achievement and potential to the UK.
Recently, Prof. Haas has become one of the most visible and most cited researchers in the area of optical wireless communications. For example, according to Google Scholar, his h-index is 92 and his work was cited more than 43,000 times, with more than 30,000 citations in the past 5 years. He has published more than 600 peer-reviewed papers. Professor Haas has been listed by Clarivate (Web of Science) as a Highly Cited Researcher in the field of Computer Science continuously since 2017. His work has received several recognitions. For instance, he was co-recipient of the 2015 Jack Neubauer Memorial Award from the IEEE Vehicular Technology Society, the 2015 EURASIP Best Paper Award of the Journal of Wireless Communications and Networking, IEEE International Communication Conference (ICC) best paper awards in three consecutive years from 2016 – 2018. ICC is the international flagship conference in the field of communications. In 2019, he received the James Evans Avant Garde Award of the IEEE Vehicular Technology Society *for pioneering contributions to multiple antenna transmission systems and optical wireless communications, in particular spatial modulation and LiFi (Light Fidelity).* He was the winner of the Enginuity Connected Places Innovation Award, in the UK in 2021. Professor Haas has also been selected as one out of 10 Recognising Inspirational Scientists and Engineers (RISE) Leaders in the UK in 2014.

He holds 44 awarded patents and is one of a few people in the world who were invited by TED Global twice. In his first invited TED talk: "Wireless data from every light bulb" which resulted from the recognition in Prof. Haensch's book: "100 Produkte der Zukunft: Wegweisende Ideen, die unser Leben verändern werden", he first coined 'LiFi' and demonstrated wireless data transmission from an ordinary light bulb to the public. His online video has been watched more than 2,754,000 times. The TIME Magazine listed 'LiFi' as one of the 50 best inventions in their November 2011 issue. Subsequently, Prof. Haas and his work on optical wireless communications featured in several international media outlets such as BBC, NPR, CNBC, New York Times, Wired UK, NewScientist, The Economist, Financial Times and CNN International. His second invited TED talk "Forget Wi-Fi. Meet the New Li-Fi Internet" where he demonstrated for the first time in public the simultaneous use of an ordinary solar panel as an energy harvesting device and high speed optical wireless data detector. This talk has been watched more than 2,827,000 times within six years.
He has received more than 100 invitations for lectures, keynotes and plenary talks. As part of his strive for wider impact, he set-up and co-founded pureLiFi Ltd which currently employs a workforce of 40 highly skilled people in the UK, Europe, Asia and the USA. He currently serves pureLiFi as the Chief Scientific Officer (CSO).
Before he started to focus on optical wireless communications in 2005, Prof. Haas had worked in radio frequency (RF) wireless communications for 10 years including several years in industry. He received a Heinz-Nixdorf Scholarship for South-East Asia and contributed to the setup of the first GSM network for Mumbai before he joined Siemens Semiconductors (now Infineon) in 1995 where he was part of a team that developed the first GSM chipset for Siemens mobile phones.

In 2006, he introduced a completely new multi-antenna transmission technique which he coined 'spatial modulation'. Spatial modulation has since been advanced by many research groups worldwide. There are currently more than 2000 research papers that have investigated a wide range of issues related to this completely new wireless transmission approach. This technology was adopted by Samsung.

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- Participation in the LpS/TiL Awards
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Glass House Garden Room, Seoul

Lichtvision Design

Sitting atop the Hyundai Mokdong Department Store in Seoul, the Glass House Garden Room provides an urban oasis for shoppers and visitors. Lichtvision and the team at Casper Mueller Kneer Architects reinterprets the traditional greenhouse to reflect modern day aesthetics. Green plant islands are located throughout the space, extending the rooftop terrace into the interior. Swarms of plant-friendly LED light fittings are placed above these islands, accentuating the plants while also supplementing additional white light required for healthy plant growth. Special attention was given during the design and LED selection process to ensure color rendering, light spectrum and lighting controls were according to biophilic design approach. The Glass House Garden Room is Lichtvision's first project with a specific emphasis on biophilic design. We look forward in continuing to explore and apply these principles in our future processes.

The Hyundai Department Store Mokdong in Seoul features the world's most famous luxury brands. While one's senses are challenged in the shopping sections below, the top floor offers a space to rest. The minimalist "Glass House Garden Room" offers a place of tranquillity for shoppers and visitors. It serves as the entrance floor to the surrounding residential towers and can play host for events and exhibitions. The space is visually broken up by islands of green plants that are embedded in the floor. A swarm of plant-friendly LED lights is placed above each island, which are intended to promote both human and plant well-being.

A Place of Recreation

Casper Mueller Kneer Architects and Lichtvision Design have designed the space as a contemporary interpretation of the traditional green house and transformed it into an oasis right in the heart of the city. They have already realized various areas of other Hyundai stores in Seoul.

In Mokdong, the surrounding roof terrace on the seventh floor was extended into the interior – daylight, however, only enters the room through the side windows. Although the ceiling is modelled after a greenhouse roof, its panels are artificially backlit. The actual ceiling above is flat and does not let in any daylight. Therefore, it was necessary to develop a lighting solution that fosters the healthy development of the plants and at the same time improves human well-being.

Swarms of Biophilic Luminaires

To highlight the plant islands, additional plant-friendly LED lights are installed above each island, enhancing both the visitors' and the plants' well-being. These fixtures float above the plants like swarms of diffuse luminous clouds. To parallel the spaces' architectural style and feel, Lichtvision specified luminaires with an industrial aesthetic and with a raw aluminium finish. Biophilic design principles were incorporated into the artificial lighting design, as Lichtvision sought to harmonize architecture with nature and place people at the centre.

To compensate for the small amount of daylight in the space, artificial light is used to enhance the health of the plants in the glasshouse. Based on the latest research, LED luminaires with a color temperature of 4,000 kelvin, good color rendering, and increased light levels were chosen. This is an optimal solution between light quality and quantity, for both human and plant physiology.

LED chips with reduced red-light component were used to avoid overstimulation and to avoid creating a stressful growth environment for the plants. In addition, the illuminance levels were designed to meet the plants' needs while avoiding glare to visitors.

Sustainable Light for Well-being

The "Glass House Garden Room" combines a modern aesthetic with a state-of-the-art approach to spatial design and lighting, that is suitable to promote plant growth. It brings natural elements into a space with the intended purpose to enhance the occupants' well-being.

Modern lighting practices and approaches give designers a way to realize this. This is Lichtvision's first foray into biophilic design, approaching nature-oriented spaces with the intended focus on occupants' well-being. It is thus an important milestone for the design studio to evaluate the latest research results in practice, to help steer future developments and to be able to meet challenges such as sustainability even better in the future.

Typology: Public/Retail/Mixed Use
Scope of Work: Artificial Lighting
Start & Completion: September 2020 – May 2021
Location: Seoul (Mokdong), South Korea
Size: 1500 m^2

Client/Owner: Hyundai Department Store
Tenant/User: Hyundai Department Store
Project Lead: Lichtvision Design; Karen Ihlau, Design Director and Paolo Cocconi, Project Designer
Architect/Designer: Casper Mueller Kneer Architects **Photographer:** Rohspace
Renderings: Casper Mueller Kneer Architects

Links:
https://www.lichtvision.com/projects/public-buildings/garden-conservatoryseoul-south-korea.html
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http://www.lichtvision.com

LICHTVISION DESIGN

The plant islands, the industrial-looking luminaires and the backlit ceiling create an exciting contrast.

The spacious area of the "Glass House Garden Room" can be used for events, exhibitions or as a relaxing oasis.

What the Lighting Industry Needs to Know about the EU Ecodesign and Energy Labelling Regulations

Elena SCARONI, Policy Director at LightingEurope

The requirements of the new EU Single Lighting Regulation (SLR) (i.e. Ecodesign Regulation for lighting) and the Energy Labelling Regulation (ELR) apply since 1 September 2021. Both have significant consequences for the lighting industry.

The SLR sets product-specific performance requirements for energy-using and energy-related products, whereas the ELR lists the labelling requirements for selling these products on the EU market. In February 2021 several additional requirements and corrections were introduced in both regulations: Regulation (EU) No 2021/341 amends the SLR and Regulation (EU) 2021/340 amends the ELR.

ELR applies to light sources only, while SLR applies to light sources and separate control gear, and luminaires (now generally identified as containing products) are addressed only indirectly. Nevertheless, luminaire manufacturers must review the rules and ensure their products comply with the new requirements.

LightingEurope [1] has published 3 sets of guidelines – on the SLR [2], the ELR [3] and on the EPREL [4] obligations for light sources – to help companies understand and apply the new rules to their products. Companies that are members of LightingEurope or its member lighting associations benefit from free access to the guidelines.

Ecodesign – Improving Product Performance

The Ecodesign Regulation (SLR) establishes EU-wide rules for improving the performance of light sources and separate control gear.

The SLR definition of a light source includes lamps, modules, and even some containing products. A containing product is defined as a product containing one or more light source(s), or separate control gears, or both. This can include not only luminaires, but also light sources contained in household appliances or furniture. The supplier of a containing product must ensure that the light source and separate control gear used in their containing product complies with all relevant EU legislation – including the SLR and the ELR.

The SLR sets minimum mandatory requirements for energy efficiency, and any product that fails to meet these requirements will be phased out, starting with products like CFLi lamps and halogen R7s > 2700 lm lamps on 1st of September 2021. As a result of this phase-out, these light sources will need to be replaced with new energy-efficient light sources and lighting installations will have to be renovated.

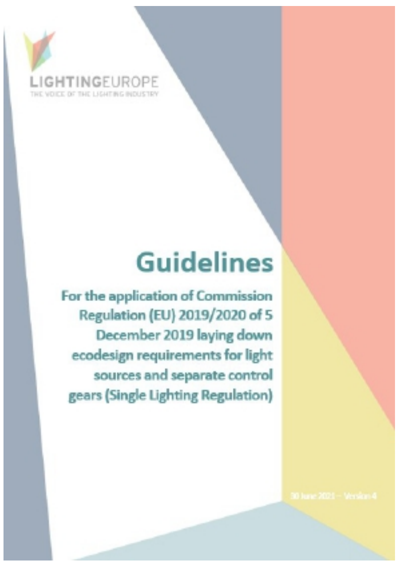
The SLR introduces several new elements related to the circular economy. For example, manufacturers, importers, and authorised representatives of containing products must ensure that light sources and separate control gears can be easily replaced using commonly available tools and without permanently damaging the containing product. They also need to ensure that light sources and separate control gears can be removed without being permanently damaged for verification purposes by market surveillance authorities. If the light sources cannot be removed for verification without damaging one or more of them, then the whole containing product must be tested as a light source and must comply with the requirements for light sources set out in the SLR and the ELR.

The SLR also requires that manufacturers, importers, and authorised representatives of containing products provide information about the replaceability or non-replaceability of light sources and control gears by end-users or qualified persons.

LightingEurope has developed pictograms with the required information on replaceability / non-replaceability – they are freely available on the LightingEurope website for all companies to download and use.

ELR – Empowerment through Information

The ELR addresses light sources, which are defined as in the SLR to include lamps, modules, and even some containing products – please note that since 25 December 2019 there is no energy label requirement for luminaires.



The Regulation requires that specific product information be provided via an energy label that includes the rescaled energy classes: the new classes are set from A (most efficient) to G (least efficient) and will gradually replace the current system of A+++ to G energy labels. It also requires that the manufacturer provides information on the product's class, along with other relevant technical information.

As the Regulation applies to the entire supply chain, there are different requirements for what information must be provided by whom.

Suppliers (i.e. manufacturers, authorised representatives, and importers) must for example place an energy label on the packaging of all independently packaged light sources.

Dealers (i.e., retailers), on the other hand, are subject to a separate set of requirements. For instance, advertisements promoting a product must include not only that product's energy efficiency class, but also the range of energy efficiency classes listed on the label.

For lamps already on the EU market and which are sold by retailers, a rescaling of the energy label is required. Retailers who are selling light sources online had 14 working days to replace the old energy labels with the new labels displayed in their online shops. This deadline applies to the electronic documentation of online sales and not to physical shops. Retailers still have 18 months (until 1 March 2023) to replace existing labels on light sources with a rescaled label on the physical product itself; this is because any stock of lamps already on the EU market with the old energy label printed on the packaging can be sold until 28 February 2023.

For luminaires, the dedicated luminaire label was discontinued on 25 December 2019. The ELR also covers light sources placed on the market in a containing product (e.g. a luminaire which contains a light source): as of 1 March 2022, information must be provided on the energy efficiency class of the contained light source, using a specific sentence. No light source energy label is required, and no light source energy label can be used on a containing product. If a luminaire does not contain a light source, it is not in the scope of the Regulation and does not have to comply with this requirement.

An energy label can only be shown, and must be shown, on a luminaire if the supplier has identified and verified this luminaire as a light source and has therefore also registered the required information on the EPREL database.

EPREL Obligations for Light Sources

The ELR also requires that all the information included on a product's energy label, in its product information sheet and in its technical documentation has to be entered into the European Product Database for Energy Labelling (EPREL) before the product can be placed on the EU market.

The European Product Database for Energy Labelling (EPREL) is the common database for information on the energy labelling of products sold in the EU, including lighting. The database consists of a public part accessible to all consumers, and a compliance part accessible only to Member State market surveillance authorities and the European Commission.

The LightingEurope guidelines on the EPREL database explain who in the supply chain needs to upload what information to the EPREL database and by when, including:

- a clarification of the scope of the EPREL database including when it is necessary to register containing products to be tested as a light source
- the values to be uploaded to each part of the EPREL database with a detailed explanation for each value
- a non-exhaustive list of harmonised standards.

The EPREL guidelines also include an excel template to help companies upload information directly to the compliance part of the database.

The Voice of the Lighting Industry

As the voice of the lighting industry, LightingEurope is dedicated to helping companies understand and apply these complex new rules.

The LightingEurope Guidelines on the SLR, the ELR and the EPREL database are available to download or order on the LightingEurope website.

To learn more about how LightingEurope can help you navigate regulatory changes and ensure you have the information you need to make informed investment decisions, visit us at www.lightingeurope.org. ■

Author: Elena SCARONI

Elena Scaroni joined LightingEurope as Policy Director in September 2016 and is responsible for policies related to Sustainability and the transition to LED. She has led the advocacy work on behalf of the European Lighting Industry on the latest Ecodesign Regulation for light sources in the legislative debate between the European Commission, the Member States and the European Parliament. Prior to LightingEurope, Elena worked for 8-years at the European Institutional Affairs of Enel, a multinational energy company for electricity and gas. She was responsible for the relations with the European Parliament on policies related to environment, climate, energy, consumers and Corporate Social Responsibility. Elena started her career as an Advisor on International Cooperation for Development, at the Italian Red Cross in Rome and in Kenya for the NGO "Ibo Italia" (the Italian branch of the International Building Organization). Elena studied in Rome and Paris, holds a master's degree in law and is specialised in European Affairs.

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[1] https://www.lightingeurope.org
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[3] https://www.lightingeurope.org/ecodesign-guidelines
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When Human Centric Lighting Gets Personal: p-HCL

Prof. Dr. Ir. Jean-Paul LINNARTZ[1,2,email], Research Fellow at Signify and Professor at Eindhoven University of Technology and Charikleia (Chara) PAPATSIMPA, Ph.D.[2,email], PostDoc Researcher at Eindhoven University of Technology; The Netherlands

Light has an unquestionable effect on human health, physiology, comfort, productivity and mental wellbeing. Through its pivotal role in entraining circadian rhythms, light exposure orchestrates the daily rhythms in several physiological phenomena. Well known examples are the influence of light on our sleep/wake cycle, hormone secretion, and subjective alertness and performance. The use of mathematical models to understand and to predict the effects of light on this complex physiological system is becoming increasingly accepted in scientific literature. That raises the question of when and how these insights in human aspects of light find their way into lighting control algorithms.

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The central biological clock in the brain is responsible for modulating the daily rhythms in several physiological phenomena, including the sleep/wake cycle, hormone secretion, gene expression and subjective alertness and performance in humans [1]. As such, the biological rhythm influences the capabilities of a human throughout a 24-hour cycle. For example, sports and muscular performance are optimal in the subjective early evening [2] and circadian rhythms have been found in neuropsychological processes such as attention, working memory, and executive functions [3].

Light is the predominant 'zeitgeber' (time giver) that entrains the biological clock to the 24-hour light and dark cycle. The central biological clock, in turn, maintains a temporal synchrony between internal periodic cycles and the external environment that is thought to enhance overall organismal function and survival [4].

Despite the growing scientific understanding and the wealth of insights into how light influences our wellbeing, our comfort and our productivity, this understanding is still barely exploited in lighting control systems. Can models of human experience of light be quantified, such that automated systems can interpret these? Future smart lighting systems may predict what the effect of a certain light recipe will be by tracking a digital twin of the user. That would allow an optimization of lighting design across various aspects and functions of light, such as a healthy trade-off between the functional (the ability to perform a task), emotional (related to an environment that people perceive intuitively as comfortable or safe or simply gives us a good feeling) and biological effects of light (desired alertness and sleep quality at night). It was the vision at the start of the Optilight project at Eindhoven University of Technology, to optimize the light settings based on quantified models for the impact of light on people.

"Human behavior and experience cannot simply be described by a set of mathematical equations." During the early phases of the project that was a frequently heard critique on the ambition of Optilight. On the other hand, lighting control algorithms that are used throughout industry regrettably do not use scientific insights on biological aspects of light to a full extent, while much can be gained. In adjacent research areas, mathematical models of human perception are commonly used in algorithms. In fact, this has led to great innovations: taking a smartphone JPG selfie, listening to MP3 Internet radio, or watching streamed video, as with Netflix, would not have been possible without elaborate models of how people perceive sounds and images. While current mathematical representations of the physiology of sleep and circadian system have been validated widely across studies in both controlled lab experiments and real-life situations, their practical application in automatic lighting system remains limited.

However, in the past years, the lighting research community has gained much more confidence in the use of quantitative mathematical circadian models. Major journals such as IEEE Transactions on Biomedical Engineering, e.g. [5,6] and Nature Scientific Reports [7,8] are accepting theoretical work to predict the effect of smart lighting control on humans in a quantified, mathematical way. A key breakthrough is that mathematical abstraction lends itself much better for use in lighting control algorithms than a repertoire of user tests under controlled lab conditions.

To use such perceptual models for lighting control, multiple scientific challenges remain: One of the major limitations of existing circadian models is that they are not tailored to individual physiological characteristics. Existing models are based on general population data, such that they represent the average responses of physiological processes and use the same parameter values for all individuals. Yet, there are large inter-individual differences in circadian and sleep/wake-related factors, which is important to consider as HCL systems may want to use the models to predict individual responses to input. The magnitude of such individual differences is often considerable and comparable to the effect sizes of many experimental and clinical interventions [9]. Publications on user tests often struggle to identify statistically significant effects, intentionally limit the number of variables and parameters to avoid overfitting on too small data sets, and carefully describe the restrictions of the applicability of the findings.

Secondly, sensor data come with large inaccuracies, particularly if privacy and comfort of the user prohibits intrusive observations. The light exposure of office workers involves aspects such as task area intensity, luminance of walls and of ceilings, spatial uniformity and other parameters of the distributions, such as glare, which may require processing of camera images if done accurately. Also, context is known to highly influence whether a light distribution is appropriate but counting the number of people in a room or detecting their activity may conflict with privacy concerns. Monitoring full sleep-wake patterns in daily life, to take circadian effects of light into consideration would be far too obtrusive, even if one refrains from using clinical standards. Thirdly, light's effects on visual experience, on alertness, and on sleep all follow temporally, spatially, and spectrally different pathways [10].

Nonetheless a wealth of insights is available from studies in controlled lab conditions. The non-image forming effects of light on circadian rhythms are even modeled as a set of differential equations, so this gives a starting point. Building upon existing knowledge, Optilight has successfully tested the feasibility of creating a "digital twin" of the human that adheres to validated chronobiological principles and that on a day-to-day basis learns about an individual's biological clock phase and their chronotype. The self-learning digital twin is built upon existing physiological models of the circadian system but is continuously updated with data from sensors monitoring the real user. This real-time data is fed back to the initial mode and continuously updates it. In that way, key model parameters are calibrated to match the user, i.e., to capture his/her personal responses and preferences to light exposure and to refine the digital twin model.

However, as observations in real-world systems come with large uncertainties and "noise", the approach needs to account for statistical deviations rather than deterministically predict effects. For personalized HCL, Optilight extended the digital twin concept into an approach that evaluates multiple noisy variants in parallel and to regularly pick the most likely variant. This concept is known in the field of statistical signal processing as a particle filter [11,12].

This digital twin of one's biological clock extended with a particle filter was used to predict and to anticipate the impact of various light recipes. Future light recipes are tested on the digital model (instead of on the real person), and this allows the pre-selection of the optimal light recipe for the individual based on his/her particular needs and his/her responses and sensitivity to light input. The latter are learned from past observations of reactions to light exposure. Different people have different needs and are exposed to different settings. A lighting recipe designed to make an evening person wake up earlier in the morning preferably is not the same as the lighting recipe for a morning person.

For example, It is well proven that late evening and night light delays the circadian wake propensity rhythm and as a result people that are exposed to bright evening light have late spontaneous sleep and wake-up times. For an evening person that effect can be detrimental as they already have a clock that runs at a slower pace and receiving light in the wrong time of the day can shift their sleep schedule even later. This negative effect of evening light on sleep schedule can to some extent be offset by increasing illuminance during office hours, especially during the first part of the day that light is more biologically effective. As a result, an optimal lighting design for an evening person is typically characterized by a boost of light exposure in the first part of the office day, followed by a second boost later in the early evening (**Figure 1**). However, such a recipe could be counter-productive for a very morning person. Morning people typically have a clock that runs at a fast pace. This would mean that such people should not be receiving light in the late afternoon because their clock is already in a phase where light delays the clock. As a result, the second late afternoon boost would be counter-productive for their circadian health and sleep.

Results up to now show that a "one size fits all" approach to Human Centric Lighting cannot fully deliver the significant benefits that improved personalized lighting may yield. What works very well for one individual may be counterproductive for others.

For the evaluation of HCL systems that must work without personalized user data, Optilight similarly modelled a population of digital representatives, but this time each digital replica was given its own parameter set, e.g., a specific intrinsic circadian period and chronotype, and its own light input pattern, e.g., evening light from a computer screen. Interestingly such mathematical exercises deliver recipes much faster than lab experimental studies with human subjects. But such theory-based results need to be treated with caution. In Optilight, the team cooperated with experts on environmental psychology and human technology interaction research: Prof. Yvonne de Kort initially was skeptical about the use of mathematical models for predicting human behavior. "But we see that the biological clock models can be powerful in explaining differences in the effect of light recipes on sleep timing. Optilight analyses, for instance, showed that a light recipe's positive

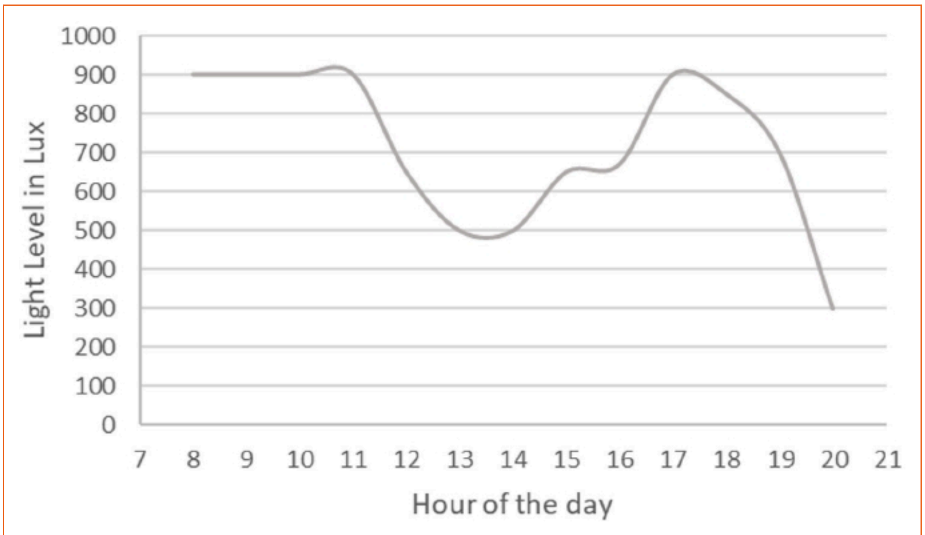

Figure 1: Optimal lighting design during office hours for an evening person (intrinsic circadian period greater than 24 hours).

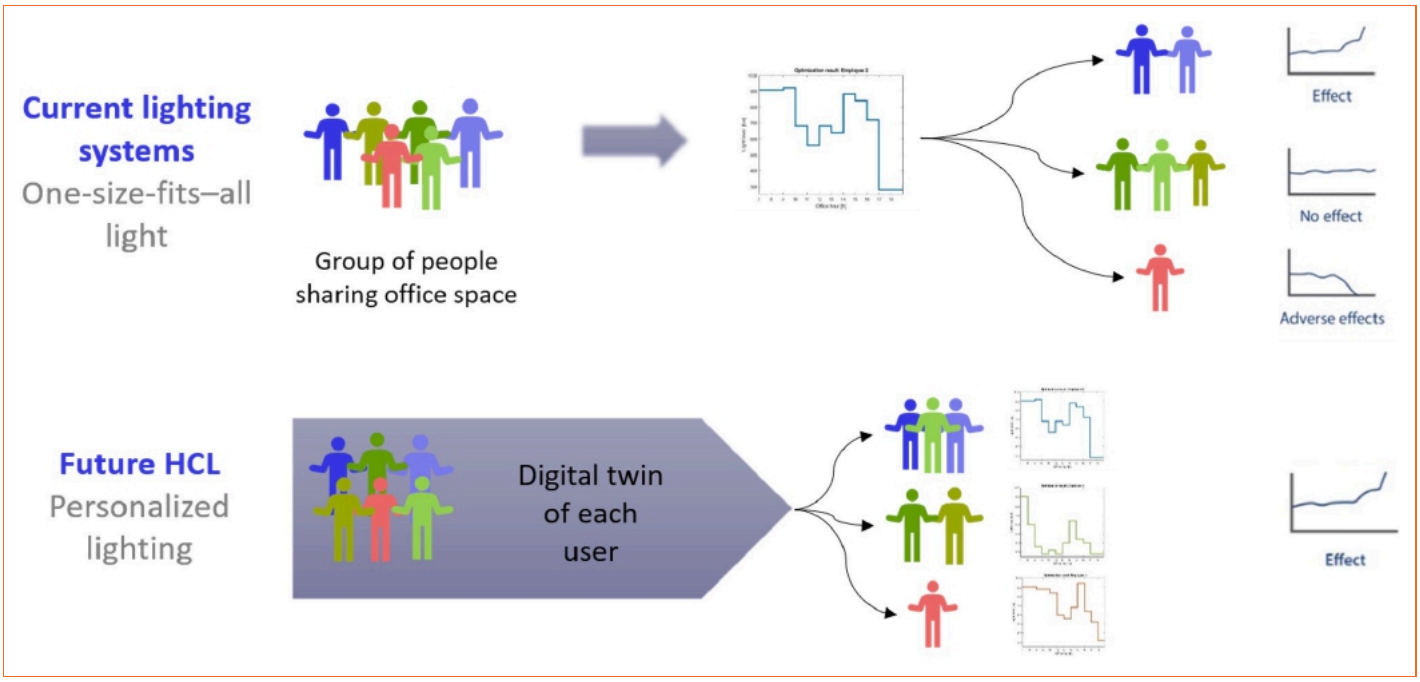

Figure 2: The digital twin concept for personalized human centric lighting. **a)** Same lighting recipe is applied to all people sharing the same office. Since people might be in a different phase of their circadian rhythm and might have different needs, this light recipe might be beneficial for some subset of the population, may have no effect on another part of the population and might be counterproductive for others. **b)** The digital twin of every person is constructed in multiple copies, based on physiology-based models and user specific data. Each twin inherits the same mathematical structure, i.e., the same underlying model, but is computationally tested with different lighting recipes. The light recipe that has the best effect on the digital twin is selected for that person. Light recipes can be grouped for subgroups of people that share similar characteristics.

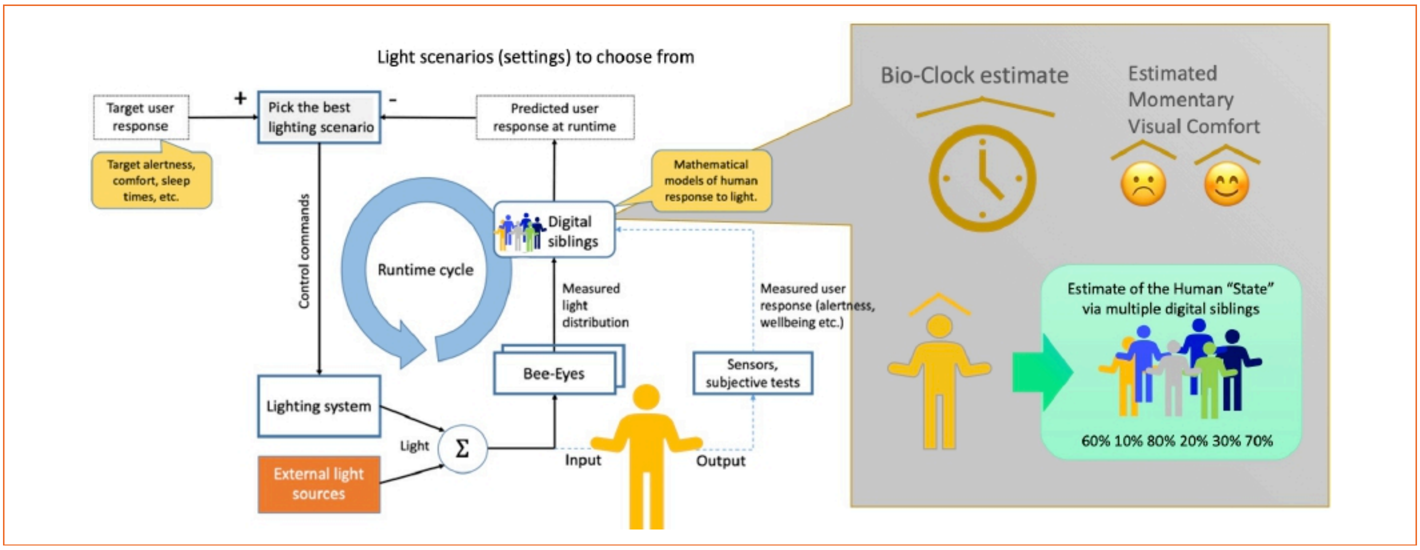

Figure 3: System concept of a bio-clock aware lighting control system. The system monitors a person's real-time light exposure which is the main input to the biological clock. Also, the person's response to light exposure (output) is monitored, which could be via body worn sensors. These inputs and outputs are used to track an estimate of the human state (bio clock, intrinsic parameters) in "digital siblings". These digital siblings are computer models that can we used to fast forward potential light recipes and to evaluate their acute and future impact on the real human. The Chinese hat above the clock or above an emotion is used similar to the mathematical notation to denote an estimate that the system makes of the user experience and the phase of the bio clock. The digital siblings do not know the real user satisfaction but make a digital estimate.

effects on a specific subset of participants can be counterproductive for other participants. This should now motivate us to develop similar models for also predicting acute alerting effects, and for predicting users' preferences in terms of the visual experience".

A lesson learned is that Human Centric Lighting is more effective if it is personalized; by taking specific preferences and chronobiological parameters of the individual into account, light recipes become significantly more effective. But as the impact of light exposure is a slow and subtle process, the effects of light on the specific users are preferably tracked over longer periods of time. One cannot, and preferably should not aim to drastically shift circadian phase and sleep cycles. A second important lesson learned is that research in psychological research can be designed such that they more easily allow for the subsequent development of mathematical abstractions.

HCL systems that cannot use personalized data can nonetheless be optimized by evaluating the effects of a light recipe on a larger population instead of only on one population-average reference person. For instance, instead of only optimizing for the average person, one may avoid recipes in which too large fractions of the population would see adverse effects [7].

Bio-Clock Aware Office

These concepts can be used to create a smart office [11,12,13] with a personalized bio-adaptive office lighting system, controlled to emit a lighting recipe tailored to the individual employee. Ideally, the chronobiological models are used in a personalized optimization algorithm that finds the best office lighting profile taking the specific preferences and parameters of the individual employees into account to achieve circadian alignment to the 24-hour cycle.

The system aims to support employees' circadian rhythm and ensure that they receive the right light at the right time of the day. **Figure 4** presents results of the optimization for three different employees that share the same office but have differences in their chronotypes and/or in their evening activities.

The resulting profiles share some common characteristics. For example, they recommend higher light levels early in the morning (say, between 8:00 to 9:00 AM). This theoretical finding appears to agree well with several studies with human subjects. Such studies confirm that daytime light exposure supports wellbeing and improves sleep. All profiles also involve a dimming in the light exposure during the middle of the day. During this part of the day, light is less biologically effective in the sense that increasing light during that time does not lead to any noticeable circadian phase shifts. One has to note that light during the mid-day is still able to introduce shifts in the circadian pacemaker; however, its effect is less compared to light during the early morning or late afternoon. The lights are dimmed mainly to conserve energy. Interestingly, during the afternoon the derived recommended light profiles differ among people. If someone is likely to be exposed to enhanced light levels later in the evening, for example someone that typically has a late dinner with the family, the resulting light recipe shows an increase in the light levels in the early afternoon (**Figure 4**a). Although this result might seem contradictory, it is supported by experimental studies that have shown that the effects of late evening exposure on physiology and sleepiness are reduced when this light exposure is preceded by early evening light [16]. This afternoon boost is less prominent when one does not have extended light exposure later in the day (**Figure 1**b). The timing of this afternoon light exposure also differs by individual. For example, a person with an earlier chronotype (**Figure 4**b) receives the afternoon light 'boost' at an earlier point in the afternoon because by tracking the user with wearables one can identify the exact circadian phase that light has the boosting effect.

Optilight[1] was jointly funded by the Dutch NWO and by Signify. The team made scientifically recognized steps towards using these insights and knowledge from chronobiology in advanced lighting control, but also verified to what extent these principles can be used in HCL solutions. Signify developed NatureConnect as a human centric lighting system built on proven biophilic design principles to reconnect people to the outside world. The system mimics the natural patterns of daylight to create comfortable, engaging and attractive indoor environments. In the Optilight project, the chronobiologic oscillator models have been used to review and refine these patterns with the potential impact on sleep in mind. In fact, also without personalized, possibly privacy-invasive tracking of the users, the models can be used to advantage.

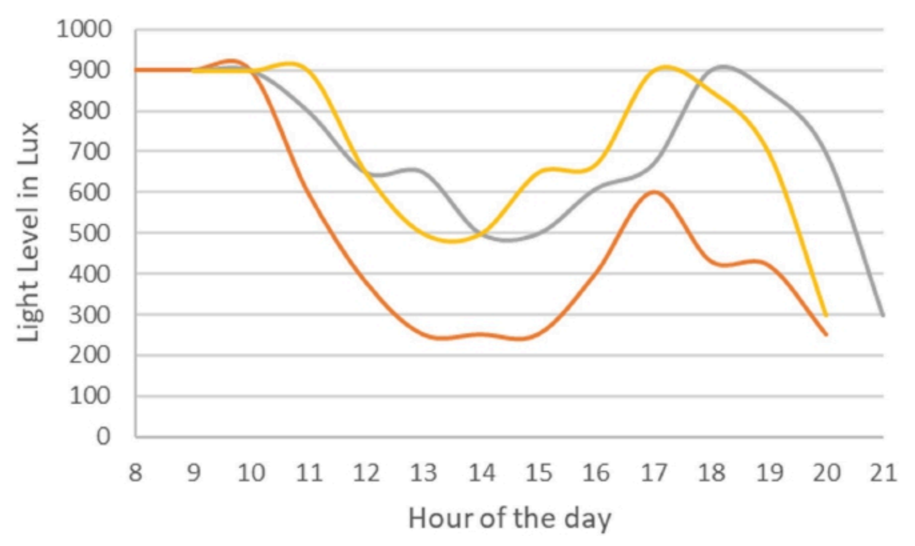

Figure 4: Optimal lighting schedules during office hours to shift the employees wake-up time.
(a, gray) Employee 1 receives light during the early morning (phase advancing region), followed by a dip in the light levels during the mid-day (dead-zone in the biological clock), followed by an increase during the early evening (amplitude attenuation region); **(b, orange)** The second employee receives light during the phase advancing region (early morning), followed by a larger dip in the light levels during mid-day, followed by a moderate increase during the early evening; **(c, yellow)** The third employee's afternoon light boost is shifted by approximately an hour compared to employee 1.

[1] Mathematical Optimizations for Human Centric Lighting. https://www.nwo.nl/en/projects/14671.

Multidisciplinary HCL in Eindhoven

Within the Intelligent Lighting Institute of Eindhoven University of Technology, the expertise on human interaction, and signal processing, the role of light in buildings and the architecture of lighting control systems is combined in joint projects across multiple departments. This created a unique basis for a project like Optilight. It is a clear example of combining existing biological knowledge on the effects of light on human physiology and behavior with machine learning for the design of smart self-learning algorithms. The research expertise of statistical signal processing allows the use of knowledge and insights from human perception and physiology to develop algorithms. It avoids black-box approaches where algorithms must start building artificial intelligence from scratch. In the field of chronobiology and lighting, hundreds of papers describe the impact of light under various conditions. It would be naïve not to use that expertise explicitly in the algorithms. ■

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Figure 5: Bio-clock aware office: A Digital Twin tracks the circadian state and light experience of each user. The virtual twin runs invisibly in the background but is shown here as an explicit projected info panel on the wall for illustration purposes only.

Jean-Paul LINNARTZ, Prof. Dr. Ir.

Jean-Paul Linnartz is a Research Fellow at Signify and a Professor at Eindhoven University of Technology in the Netherlands. His research addresses intelligent lighting systems and optical wireless communication (LiFi). Previously, with TU Delft and the University of California at Berkeley, he worked on wireless radio communication (he introduced MC-CDMA). As principal scientist and later as senior director at Philips Research, he worked on electronic watermarking and on anonymous biometrics. His work is cited over 12,000 time (GS) and led to more than 75 granted patents, some of which are the basis for three ventures. He is a Fellow of the IEEE for leadership in security with noisy data and these ideas secure more than 300 Million IoT devices.

Charikleia (Chara) PAPATSIMPA, Ph.D.

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LUXTECH Offers First Compelling Flex Modules Designed to Replace Traditional Rigid Modules: LUXroll (UL Listed)

LUXTECH, luxtech.com

The Indirect Costs of Using Rigid Boards Make Switching to Flexible LED Modules a Compelling Choice

As rigid modules have long dominated the LED module market, OEM fixture manufacturers have dealt with the increased costs and complexity of managing an unnecessary number of module SKUs (Stock Keeping Units) – 5.5", 11", 22", 44", 47" etc. These high SKU counts make it more challenging to leverage high volume buying power for any individual board, especially for high mix manufacturers. Clever decisions about which module lengths to inventory can only go so far, and installation time increases as operators have to trim, install, and wire multiple rigid modules together in a single fixture.

With SMT machines currently limited to 4 foot build lengths, any fixture longer than 4 feet requires multiple rigid boards. Additionally, the discreet board lengths limit the variety of luminaire lengths that fixture manufacturers can offer to their customers. Using custom rigid module lengths presents additional risks by making inventory less versatile to be used in different products, often leading to undesirable lead times when frequent changes in fixture demand trigger supply management challenges. These overhead costs of inventory management and precious floor space compound quickly when utilizing rigid modules in many lengths. Imagine a world where a single module SKU could be continuously installed in any length fixture!

LUXTECH's LUXroll Flex is the 1-SKU-Fits-All Solution

LUXroll gives fixture OEMs the ability to reduce both luminaire costs and lead times by delivering architectural grade light with all of the additional benefits of using a single SKU in place of multiple rigid board lengths. Fixtures can be built to any length down to the half inch specification so the same module can be used across all fixture lengths for both standard and customizable product offerings (**Figure** 1). LUXroll reduces overall lead times and allows for more responsiveness to changes in demand for different fixture types and lengths. Since it is used across products, it enables OEMs to receive volume price breaks for both high and low running fixtures. Compared to installing rigid boards, LUXroll is typically twice as fast to install meaning higher throughput in manufacturing. There is never a need to wire boards together to achieve longer runs or install multiple screws per board. Inventory footprint, operating costs, and even module shipping costs are also often significantly reduced with the densely packed and reeled flex modules.

Speed of Installation: LUXroll is 2× Faster to Install Than Traditional Rigid Boards

LUXroll [1] typically improves the speed of module installation **Figure** 1 by 2× when compared to installing 2 rigid boards in fixtures >4 feet in length. LUXTECH has a video [2] showing this comparison.

View the installation video.

The high-strength 3M adhesive is simple and quick to install while simultaneously creating an excellent thermal dissipation path for the module (**Figure** 2, **Figure** 3). The tape can be lifted and adjusted when installing but provides a robust bond (**Table** 1) for long term reliability even under harsh thermal conditions.

UL Listed, Specification-Grade Performance

LUXroll has a greater thermal dissipation performance than comparable FR4 rigid modules (**Figure** 2) due to the high strength 3M thermal adhesive. As FR4 modules are driven harder and heat up, the screws can cause the board to buckle from thermal expansion which increases risk of thermal runaway and LED failure. With LUXroll, thermal contact is always maintained, and the LED junction temperature is kept well below 80 °C even at >20 W/ft with minimal heat sinking on typical fixture materials. The UL2108 listing for LUXroll holds for use even on wood substrate. Peel force data shows LUXroll's strength across a variety of materials, even at high operating temperatures (**Table** 1).

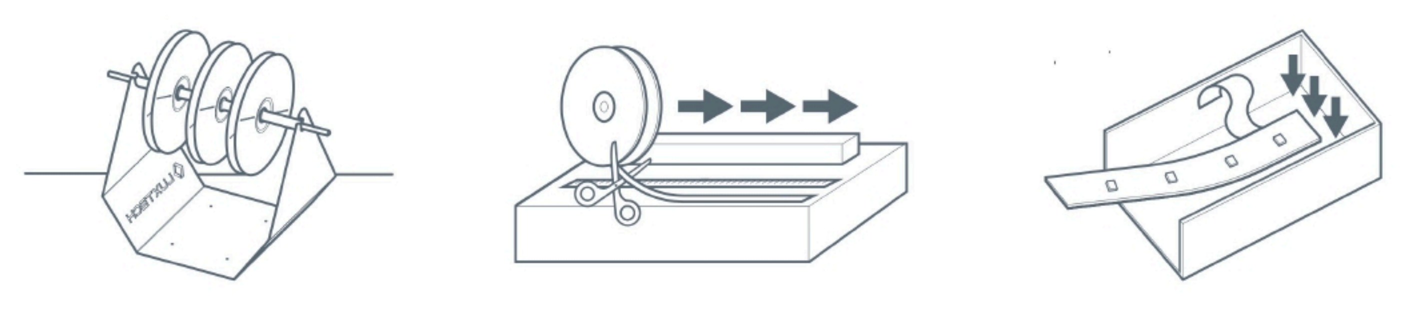

Figure 1: LUXroll Installation Process > Use LUXroll Dispenser (left) – Cut to Length (middle) – Attach to Gear Tray (right).

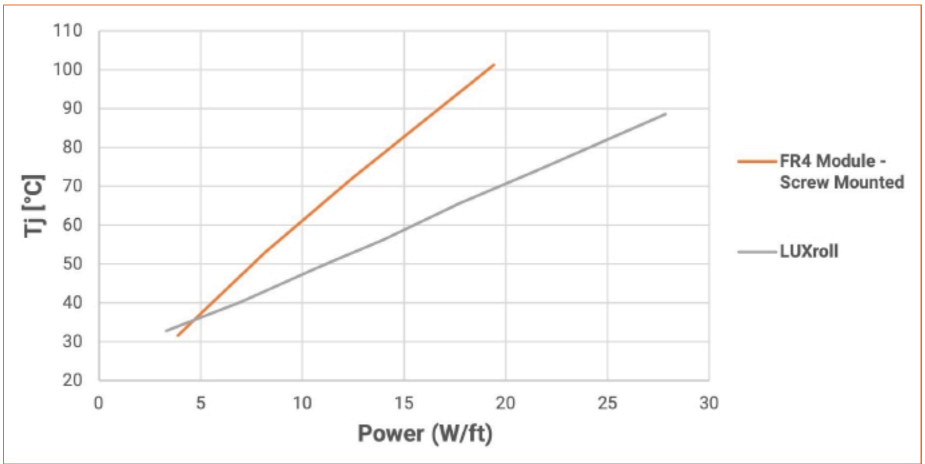

Figure 2: Thermal Perfomance Comparison (on Junction Temperature Tj) between a screw mounted FR4 module (orange) and LUXroll (grey).

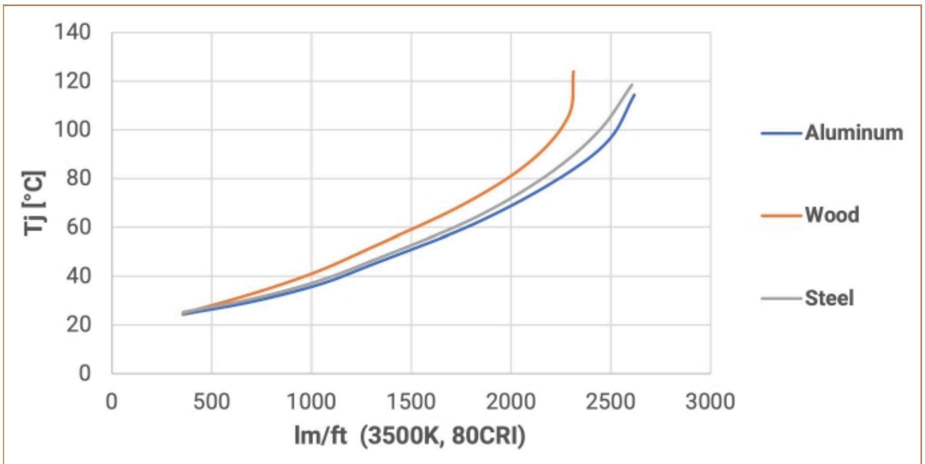

Figure 3: Material Performance Comparison (on Junction Temperature Tj) between Aluminum (blue), Wood (orange), and Steel (grey).

Substrate	Peel Force (lbf/20mm) 25C	Peel Force (lbf/20mm) 85C
Wood	7	3
Aluminum	6	5
Powder Coat Aluminum	6	5
Steel	10	5
Powder Coat Steel	6	4

Table 1: Bond Force Comparison for different materials at 25 °C and 85 °C.

LUXroll Variations

LUXroll is available in constant current white and tunable white, and constant voltage RGB and RGB+W. All SKUs are UL2108 listed to make the fixture listing process cheaper and faster. With the same form factor, swapping out any version for another is super simple. The white and tunable white options are cuttable every ½ inch while RGB and RGBW options are cuttable every 2 inches. All come standard with poke in connectors and packaged in 44 foot recyclable reels. Stocked in Philadelphia for next day shipping.

Summary: Replacing Rigid Boards with Flex Makes a Lot of Sense

As continuous reel-to-reel manufacturing techniques continue to mature in the electronics industry, continuous and flexible LED modules will become the standard in LED luminaires. There are clear benefits for versatility, volume pricing, reduced installation labor, and simplified inventory management. To learn more about LUXroll, check out LUXTECH's product videos and guides here: `https://luxtech.com/products/luxroll/`.

See the benefits for yourself and request a LUXroll sample kit [3] today. ■

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https://luxtech.com/products/luxroll/
[2] Speed of Installation Video
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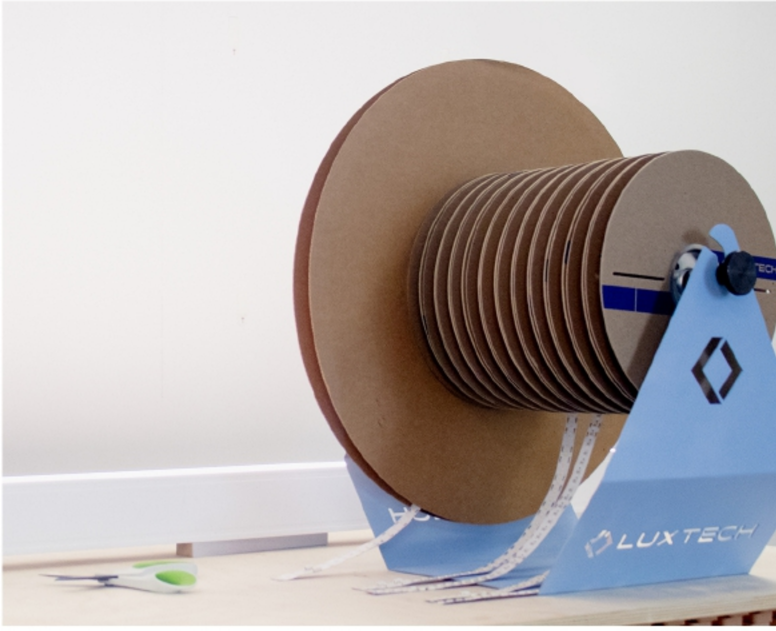

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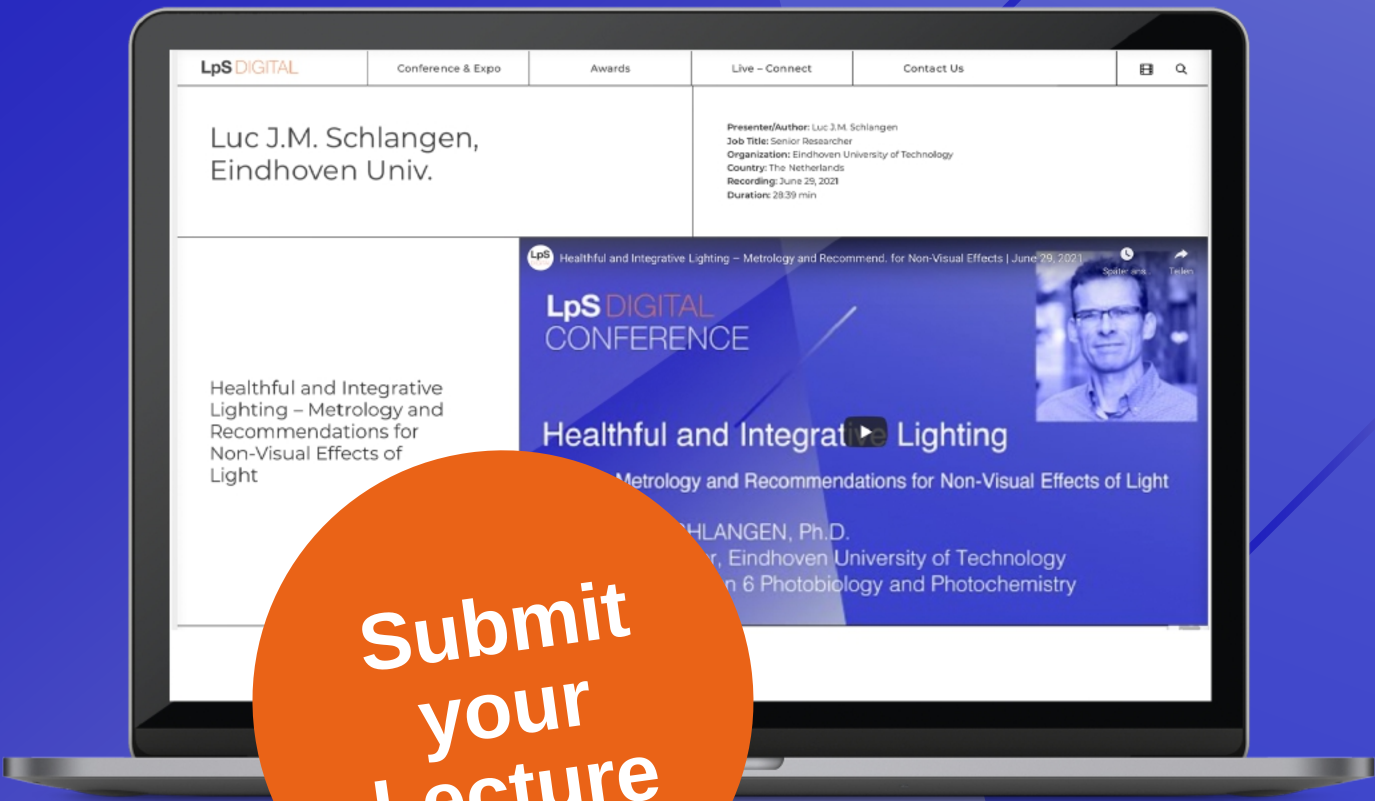

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The Virucidal Effects of 405 nm Visible Light on SARS-CoV-2 and Influenza A Virus

Raveen RATHNASINGHE[1,2,3], Sonia JANGRA[1,2], Lisa MIORIN[1,2], Michael SCHOTSAERT[1,2], Clifford YAHNKE[6], & Adolfo GARCIA-SASTRE[1,2,4,5,7(email)], PhD, Director of the Global Health & Emerging Pathogens Institute and Professor of Microbiology and Medicine at the Icahn School of Medicine at Mount Sinai

The germicidal potential of specific wavelengths within the electromagnetic spectrum is an area of growing interest. While ultra-violet (UV) based technologies have shown satisfactory virucidal potential, the phototoxicity in humans coupled with UV associated polymer degradation limit their use in occupied spaces. Alternatively, longer wavelengths with less irradiation energy such as visible light (405 nm) have largely been explored in the context of bactericidal and fungicidal applications. Such studies indicated that 405 nm mediated inactivation is caused by the absorbance of porphyrins within the organism creating reactive oxygen species which result in free radical damage to its DNA and disruption of cellular functions. The virucidal potential of visible-light based technologies has been largely unexplored and speculated to be ineffective given the lack of porphyrins in viruses. The current study demonstrated increased susceptibility of lipid-enveloped respiratory pathogens of importance such as SARS-CoV-2 (causative agent of COVID-19) and influenza A virus to 405 nm, visible light in the absence of exogenous photosensitizers thereby indicating a potential alternative porphyrin-independent mechanism of visible light mediated viral inactivation. These results were obtained using less than expected irradiance levels which are considered safe for humans and commercially achievable. Our results support further exploration of the use of visible light technology for the application of continuous decontamination in occupied areas within hospitals and/or infectious disease laboratories, specifically for the inactivation of respiratory pathogens such as SARS-CoV-2 and Influenza A.

The severe-acute respiratory syndrome corona virus 2 (SARS-CoV-2), the causative agent of the COVID-19 pandemic, is a member of the beta-coronavirus family and it emerged at the end of 2019 in the Hubei province in Wuhan China [1]. By late February 2021, more than 112 million cases had been reported while accounting for approximately 2.5 million deaths, underscoring the rapid dissemination of the virus on a global scale [2]. As a complement to standard precautions such as hand-washing, masking, surface disinfection, and social distancing, other enhancements to enclosed spaces such as improved ventilation and whole-room disinfection are being considered by segments beyond acute healthcare such as commercial offices, retail, dining, and transportation [3].

Initial guidance from health authorities such as the CDC and WHO on environmental transmission focused on contaminated surfaces as fomites[4]. Data pertaining to the survival of SARS-CoV-2 and other related coronaviruses to date has indicated that virions are able to persist on fomites composed of plastic [5], wood [6], paper [5], metal [7] and glass [8] potentially up to 9 days. Recent studies have suggested that SARS-CoV-2 may also remain viable approximately at least 3 days in such surfaces and another two studies showed that at room temperature (20–25 °C), a 14-day time-period was required to see a $4.5 - 5 \log_{10}$ of the virus [9,10].

Since the start of the pandemic, transmission of the virus by respiratory droplets and aerosols has become an accepted method of transmission although the relative impact of each mode of transmission is the subject of much debate. Nevertheless, enclosed spaces with groups of people exercising or singing have been associated with increased transmission. The half-life survival of SARS-CoV-2 in this type of environment has been estimated between 1 and 2 h [6,11,12].

Taking this information into consideration, several methods have been shown to effectively inactivate SARS-CoV-2. Chemical methods, which focus on surface disinfection, utilize 70% alcohol and bleach and their benefits are well established. These methods are also episodic (or non-continuous) meaning that inbetween applications, the environment is not being treated [13].

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In addition to chemicals, one of the most utilized methods for whole-room disinfection is germicidal ultraviolet C (UVC; ≈ 254 nm) [14]. This technology is well established [15] and has been shown to inactivate a range of pathogens including bacteria [16], fungi [17] and viruses [18]. The mechanism of action of UVC is photodimerization of genetic material such as RNA (relevant for SARS-CoV2 and IAV) and DNA (relevant for DNA viruses and bacterial pathogens, among others) [19]. Unfortunately, this effect has been associated with deleterious effects in exposed humans such as photokeratoconjunctivitis in eyes and photodermatitis in skin [20]. For these reasons, UVC irradiation requires safety precautions and cannot be used to decontaminate fomites and high contact areas in the presence of humans [21].

Germicidal properties of violet-blue visible light (380–500 nm), especially within the range of 405 nm to 450 nm have been shown as an alternative to UVC irradiation in human occupied whole-room disinfection scenarios where it has shown reduction of bacteria [22,23] and surgical site infections [24]. Although 405 nm or closely related wavelengths have been shown to be less germicidal than UVC, its inactivation potential has been assessed in pathogenic bacteria such as Listeria spp. and Clostridium spp. [24,25], and in fungal species such as Saccharomyces spp. and Candida spp. [26]. It is thought that the underlying mechanism of blue-light mediated inactivation is associated with absorption of light via photosensitizers such as porphyrins which results in the release of reactive oxygen species (ROS) [27,28]. The emergence of ROS is associated with direct damage to biomolecules such as proteins, lipids and nucleic acids which are essential constituents of bacteria, fungi and viruses. Further studies have shown that ROS can also lead to the loss of cell membrane permeability mediated by lipid oxidation [29]. Given the lack of endogenous photosensitizers such as porphyrins in virions, it was expected that efficient decontamination of viruses (both enveloped and non-enveloped) required the addition of exogenous photosensitizers [23]. With the use of media suspensions (e.g. saliva, blood, etc.) containing both endogenous and/or exogenous photosensitizers (to create the ROS required for inactivation), 405 nm light was shown to inactivate viruses such as feline calcivirus (FCV)30, viral hemorrhagic septicemia virus (VHSV) [31] and murine norovirus-1 [32] using unsafe, commercially impractical irradiance levels. This highlights the importance of answering the basic scientific questions related to viral inactivation within the context of the applied science required for clinical application. Our study specifically focused on three questions: (1) does the same wavelength of light (405 nm) that inactivates bacteria also inactivate enveloped viruses, (2) is a porphyrin rich medium required for this inactivation, and (3) can this inactivation be achieved using safe, commercially practical irradiance levels?

In the current study, we show the impact of 405 nm irradiation on inactivation of SARS-CoV-2 and influenza A H1N1 viruses without the use of photosensitizers making it directly relevant to the clinical environment. We show this using a commercially available visible light disinfection system ensuring that the irradiance used is both safe and practically achievable in a clinical setting supporting the possible use of 405 nm irradiation as a tool to confer continuous decontamination of respiratory pathogens such as SARS-CoV-2 and influenza A viruses. We further show the increased susceptibility of lipid-enveloped viruses for irradiation in comparison to non-enveloped viruses, further characterizing the virucidal effects of visible light.

Materials and Methods

405 nm Exposure System

The visible light disinfection product used in this study was a commercially available 6´ LED downlight (Indigo-Clean, Kenall, Kenosha, WI) to allow for use within a BSL-3 level containment hood. Within the hood, the distance between the face of the fixture and the sample was 10˝ – much less than the normal 1.5 m used in normal, whole-room disinfection applications. The output of the fixture was modified electronically during its manufacture to match this difference and ensure that the measurements would represent the performance of the device in actual use. This test setup is shown in a BSL-2 hood in **Figure 1**A. Note the spectroradiometer and the bottom portion of the rig (≈ 6´) used for calibration were removed during the actual study (**Figure 1**B).

Controls were placed outside the test rig but within the BSL hood as shown in **Figure 1**B. Note that this picture contains the bottom portion of the test rig to highlight the position of the radiometer. For the range of output used in this study, multiple discrete levels were created using pulse width modulation within the LED driver itself. These levels were made to be individually selectable using a simple knob on the attached control module. For reference, the amount of visible light within the 400–420 nm bandwidth, measured in $mW\,cm^{-2}$, is a measurement of the "dose" delivered to the target organism and is used to quantify this relationship similar to that used in UV disinfection applications.

To fully examine this effect, a range of irradiance values were used representing actual product deployment conditions in occupied rooms. The lowest value ($0.035\,mW\,cm^{-2}$) represents a single-mode, lower wattage used in general lighting applications while the highest value ($0.6\,mW\,cm^{-2}$) represents a dual-mode, higher wattage used in critical care applications such as an operating room.

The device was placed in a rig to ensure a consistent distance (10´) between the fixture and the samples. The output of the fixture in the test rig was measured using a Stellar-RAD Radiometer from StellarNet configured to make wavelength and irradiance measurements from 350–1100 nm with $<$ 1 nm spectral bandwidth using a NIST traceable calibration. To ensure that the regular white light portion of the illumination (which is non-disinfecting) was not measured, the measurement was electronically limited to a 1 nm bandwidth over the 400–420 nm range. The normalized spectral profile is shown in **Figure 1**C below. The absolute value of the measurement was determined using a NIST traceable calibration as previously described. Samples were irradiated with the range of wavelengths depicted in **Figure 1**C. This was deliberately done for two reasons: (1) prior work had shown that visible light disinfection was primarily active at 405 nm [33] and (2) to emphasize the applied science associated with actual clinical use where a virus in the environment could be exposed to both 405 nm and regular white light in an occupied room.

To isolate the contribution of 405 nm light, the control samples were placed outside the field of irradiation created by the disinfection product but within the biosafety hood. Accordingly, these samples were exposed to the overhead lights within the room which contained virtually no 405 nm light ($< 0.001\,mW\,cm^{-2}$).

In any assessment of viral inactivation, thermal denaturing of the organism is a concern. Older lighting technologies such as incandescent sources heat a resistive element and were widely used in a variety of applications. This creates heat at both the source and to objects within its field. Fortunately, the disinfecting light (sample) and the overhead lights in the room (control) did not use this technology and therefore contain no infrared emissions ($>$ 800 nm) a commonly known benefit associated with LED lighting. As a confirmation, the temperature beneath the disinfecting light was measured using a commercially available thermocouple during a 24-h period. During this time, the temperature at the sample position was constant at 20 °C ± 0.5 °C even at the highest disinfecting power (0.6 mW cm^{-2}).

For reference, two spectral profiles, one for traditional fluorescent lighting and the other for standard LED lighting are provided in **Figure 4** below. While both types of lighting are commonly used in the overhead lights within buildings, the lights in the BSL-3 laboratory were traditional fluorescent. As shown in **Figure 1**B, the controls were exposed only to traditional fluorescent lighting with a negligible amount of disinfecting light (< 0.001 mW cm^{-2}) between 400 nm and 420 nm. Due to the inherent differences between fluorescent and LED lighting, the standard LED spectra has a small, but measurable amount of disinfecting light (0.006 mW cm^{-2}) between 400 nm and 420 nm. As will be later shown, this amount of light can have a measurable disinfecting effect.

Cells and Viruses

Vero-E6 cells (ATCC® CRL-1586™, clone E6) were maintained in Dulbecco's Modified Eagle Medium (DMEM) complemented with 10% heat-inactivated Fetal Bovine Serum (HI-FBS; PEAK serum), penicillin–streptomycin (Gibco; 15140-122), HEPES buffer (Gibco; 15630-080) and MEM non-essential amino-acids (Gibco; 25025CL) at 37 °C with 5% CO_2. Vero-CCL81 (ATCC® CRL-81™) cells and MDCK cells (ATCC® CCL-34) were cultured in DMEM supplemented with 10% HI-FBS and penicillin/streptomycin at 37 °C with 5% CO_2. All experiments involving SARS-CoV2 (USA-WA1/202, BEI resource–NR52281) were conducted within a biosafety-level 3 (BSL3) containment facility at Icahn school of medicine at Mount Sinai by trained workers upon authorization of protocols by a biosafety committee. Amplification of SARS-CoV-2 viral stocks was done in Vero-E6 cell confluent monolayers by using an infection medium composed of DMEM supplemented with 2% HI-FBS, Non-essential amino acids (NEAA), Hepes and penicillin–streptomycin at 37 °C with 5% CO_2 for 72 h. Influenza A virus used here was generated using plasmid based reverse genetics system as previously described [34]. The backbone used in the study was A/Puerto Rico/8/34/Mount Sinai (H1N1) under the GenBank accession number AF389122. IAV-PR8 virus was grown and titrated in MDCK as previously described [34]. As a non-enveloped virus, the cell culture adapted murine Encephalomyocarditis virus (EMCV; ® VR-12B) was propagated and titrated in Vero-CCL81 cells with DMEM and 2% HI-FBS

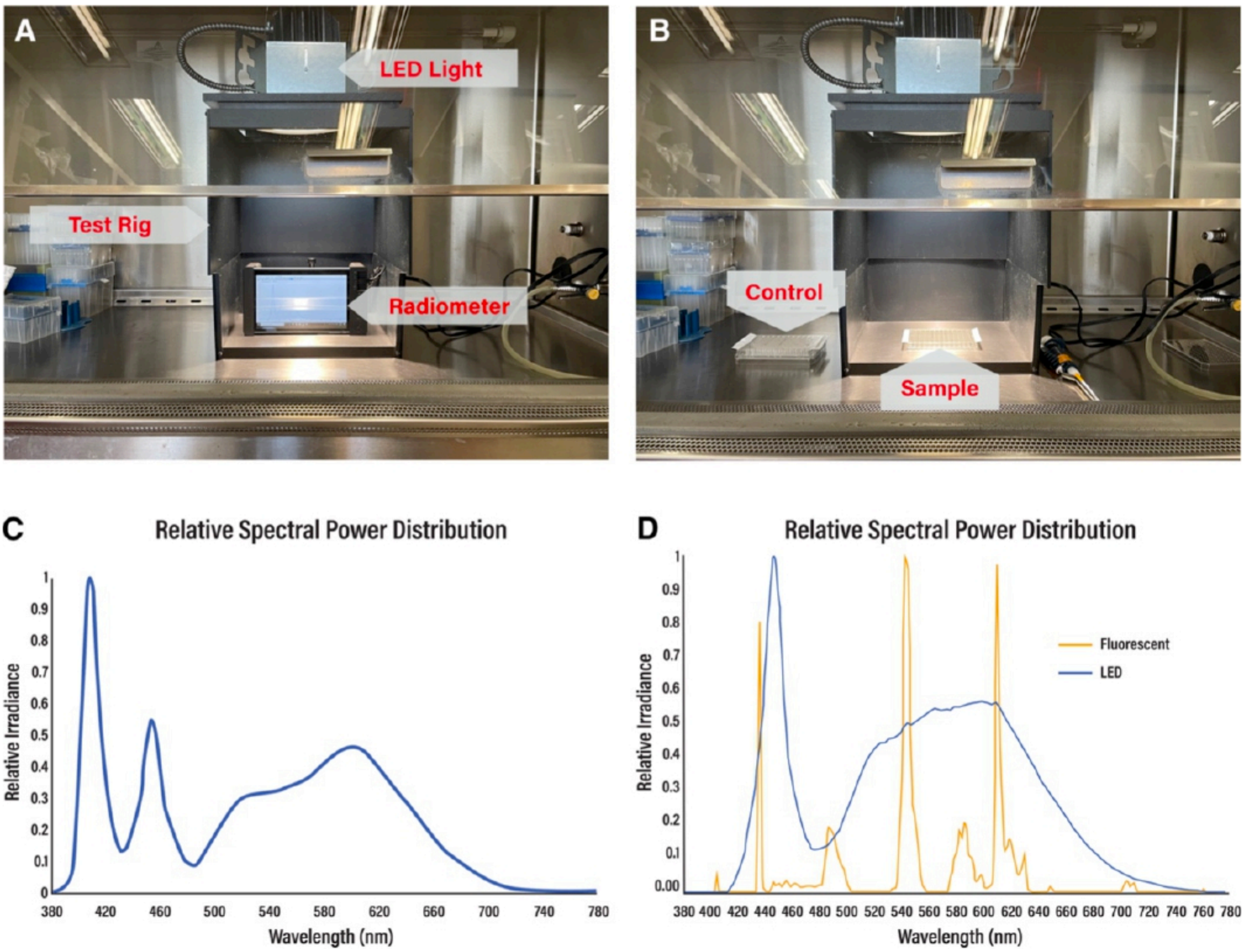

Figure 1: Inactivation device setup and characterization. (A) Test setup shown with spectroradiometer, and extension used for calibration. (B) Test setup showing the placement of the control and sample for irradiation. The bottom portion of the test rig was removed during the actual experiment to ensure the 10" distance used in the study. (C) Normalized spectral power distribution showing peak irradiance at 405 nm. (D) Normalized spectral power distribution for the fluorescent control light (non-disinfecting) and standard LED light (without 405 nm) used in the study. Each spectrum is normalized relative to its own peak value.

and penicillin–streptomycin at 37 °C with 5% CO_2 for 48 h [35].

405 nm Inactivation of Viruses

The SARS-CoV-2 virus was exclusively handled at the Icahn school of Medicine BSL-3 and studies involving IAV and EMCV were handled in BSL-2 conditions. Indicated PFU amounts were mixed with sterile 1× PBS and were irradiated in 96 well format cell culture plates in triplicates. In these studies, A starting dose of 5×10^5 PFU for SARS-CoV-2 and starting doses of 1×10^5 PFU for IAV and EMCV were used. The final volumes for inactivation were 250 µl per replicate. The untreated samples were prepared the same way and were left inside the biosafety cabinet isolated from the inactivation device at room temperature. The plates were sealed with qPCR plate transparent seal and an approximate 10% reduction of the intensity was observed due to the sealing film. The distance from the lamp and the samples was measured to be 10˝. All samples were extracted at indicated times and were frozen at −80 °C and were thawed together for titration via plaque assays.

Plaque Assays

For SARS-CoV-2 studies, confluent monolayers of Vero-E6 cells in 12-well plate format were infected (with an inoculum volume 150 µl) with tenfold serially diluted samples in 1× phosphate-buffered saline (PBS) supplemented with bovine serum albumin (BSA) and penicillin–streptomycin for an hour while gently shaking the plates every 15 min. Afterwards, the inoculum was removed, and the cells were incubated with an overlay composed of MEM with 2% FBS and 0.05% Oxoid agar for 72 h at 37 °C with 5% CO_2. The plates were subsequently fixed using 10% formalde-

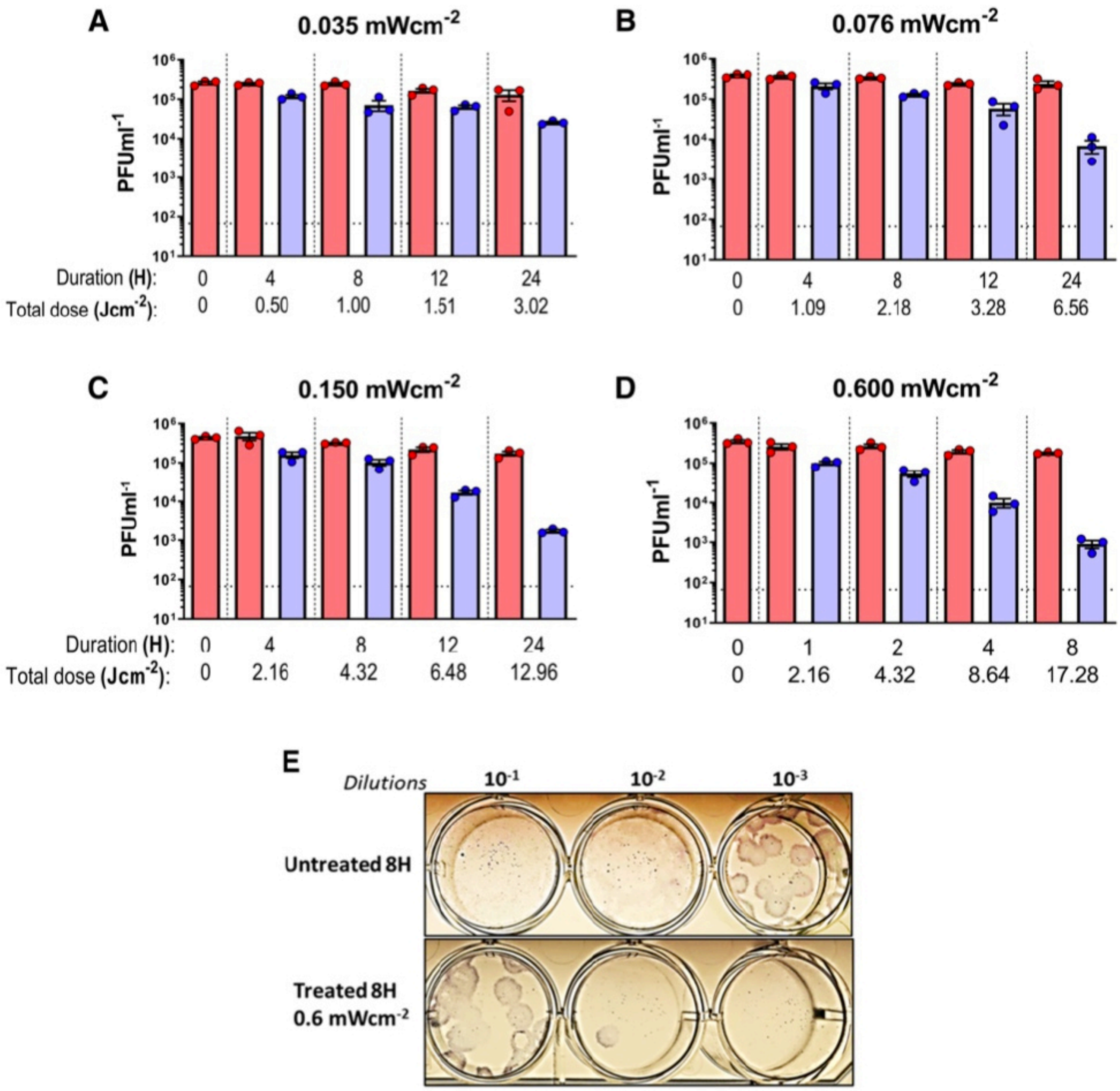

Figure 2: Dose and time dependent inactivation of SARS-CoV-2 virus in PBS by 405 nm irradiation. (A) A dose of 0.035 mW cm^{-2} or (B) a dose of 0.076 mW cm^{-2} or (C) a dose of 0.150 mW cm^{-2} or (D) a dose of 0.6 mW cm^{-2} was applied to irradiate samples at 405 nm over a course of 24 while sampling at 4, 8, 12 and 24 h (for A, B and C) or over a course of 8 h while sampling at 1, 2, 4 and 8 h (D) was done in independent triplicates. Blue bars indicate treated samples and red bars correspond to the untreated equivalent that was left at the biosafety cabinet under the same conditions while not subjecting to disinfecting irradiation. Data shown as $PFUml^{-1}$ in triplicate assessed by plaque assay. (E) Plaque phenotype comparison from one independent experiment at an irradiation dose of 0.6 mW cm^{-2}. Fixed and blocked plaques were immunostained using anti-SARS-CoV-2/NP antibody before developing using TrueBlue reagent. Data shown here are from three independent replicates (Mean + SEM).

hyde overnight and the formaldehyde was removed along with the overlay. Fixed monolayers were blocked with 5% milk in Tris-buffered saline with 0.1% tween-20 (TBS-T) for an hour. Afterwards, plates were immunostained using a monoclonal antibody against SARS-CoV2 nucleoprotein (Creative-Biolabs; NP1C7C7) at a dilution of 1:1000 followed by 1:5000 anti-mouse IgG monoclonal antibody and was developed using KPL TrueBlue peroxidase substrate for 10 min (Seracare; 5510-0030). After washing the plates with distilled water, the number of a plaques were counted. Plaque assays for IAV and EMCV were done in a similar fashion. For IAV, confluent monolayers of MDCK cells supplemented with MEM-based overlay with TPCK-treated trypsin was used and was incubated for 48 h at 37 °C with 5% CO_2. For EMCV, Vero-CCL81 cells were used to do plaque assays in 6 well plate format with an inoculum volume of 200 µl and was incubated for 48 h at 37 °C with 5% CO_2. Plaques for IAV and EMCV were visualized using crystal violet. Data shown here is derived from three independent experimental setups.

Results

Dose and Time Dependent Inactivation of SARS-CoV-2 in the Absence of Photosensitizers

The lowest irradiation dose of 0.035 mW cm^{-2} was applied for SARS-CoV-2 and when compared to the T4H untreated control, a reduction of 0.3288 $\log_{10}$ was seen as early as 4 h and after 24 h of irradiation, an inactivation of 1.0325 $\log_{10}$ (approximately 10 times reduction in infectivity) was observed for SARS-CoV-2 via plaque assays (**Figure 2**A). A slightly higher dose of 0.076 mW cm^{-2} yielded 0.4123 $\log_{10}$, 0.6118 $\log_{10}$ and 1.5393 $\log_{10}$ reduction by 4, 8 and 12 h post irradiation when compared to the respective untreated controls (**Figure 2**B). Subsequent increase of the irradiation dose to 0.150 mW cm^{-2} resulted in a reduction of 0.4771 $\log_{10}$ after 4 h which then had a 1.1206 $\log_{10}$ after 12 h. Irradiation for 24 h at 0.150 mW cm^{-2} suggested a total reduction of 2.0056 $\log_{10}$ (256 times) for SARS-CoV-2 and (**Figure 2**C). As a final experiment, a high irradiation dose of 0.6 mW cm^{-2} was used to assess the inactivation potential within a much shorter time frame. Irradiation for 1 h resulted in a reduction of 0.4150 $\log_{10}$ which reached 1.2943 $\log_{10}$ reduction by 4 h and 2.309 $\log_{10}$ (385 times) after 8 h in comparison to untreated controls samples at the corresponding times. (**Figure 2**D,E). All experimental conditions demonstrated the stability of untreated SARS-CoV-2 which was left at room temperature in PBS, as shown by the marginal reduction of viral titer over time.

Influenza A Virus is Susceptible to 405 nm Inactivation in the Absence of Photosensitizers

Given the observations derived from SARS-CoV-2, a separate inactivation study using

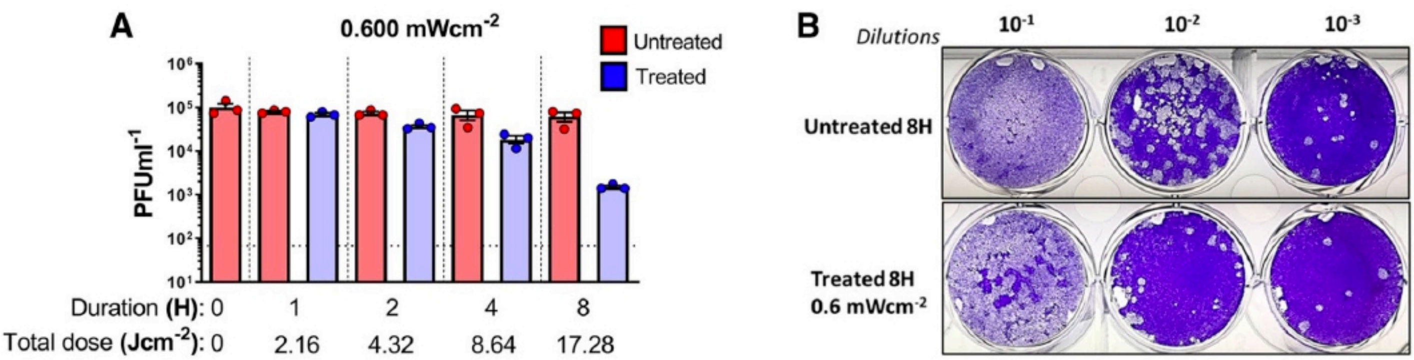

Figure 3: Inactivation of Influenza A virus in PBS by 405 nm irradiation. (A) A dose of 0.6 mW cm^{-2} was applied to irradiate samples at 405 nm over a course of 8 h while sampling at 1, 2, 4 and 8 h (done in independent triplicates). Blue bars indicate treated samples and red bars correspond to the untreated equivalent that was left at the biosafety cabinet under the same conditions while not subjected to disinfecting irradiation. Data shown as PFUml–1 in triplicate assessed by plaque assay. (B) Plaque phenotype comparison from one independent experiment at an irradiation dose of 0.6 mW cm^{-2}. Fixed and blocked plaques were stained using crystal violet. Data show in here are from three independent replicates (Mean + SEM).

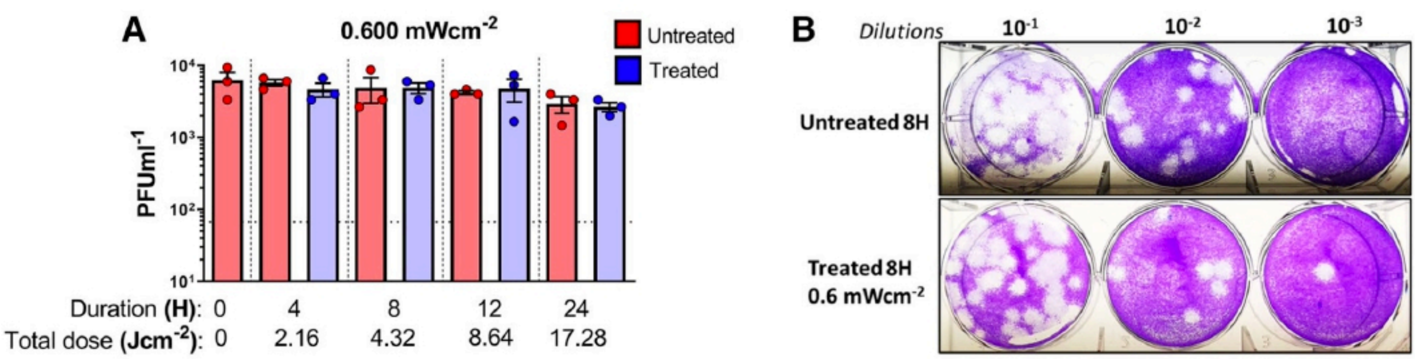

Figure 4: Encephalomyocarditis virus (EMCV) in PBS shows reduced susceptibility to 405 nm irradiation. (A) A dose of 0.6 mW cm^{-2} was applied to irradiate samples at 405 nm over a course of 8 h while sampling at 1, 2, 4 and 8 h (done in independent triplicates). Blue bars indicate treated samples and red bars correspond to the untreated equivalent that was left at the biosafety cabinet under the same conditions while not subjected to disinfecting irradiation. Data shown as PFUml^{-1} in triplicate assessed by plaque assay. (B) Plaque phenotype comparison from one independent experiment at an irradiation dose of 0.6 mW cm^{-2}. Fixed and blocked plaques were stained using crystal violet. Data show in here are from three independent replicates (Mean + SEM).

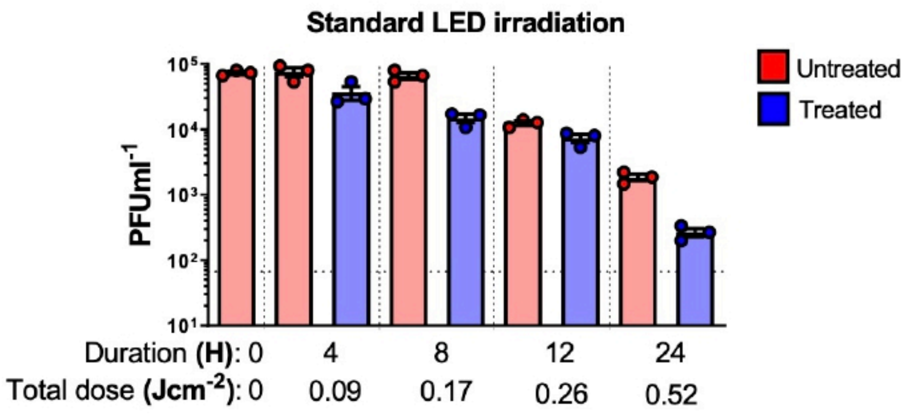

Figure 5: Inactivation potential for SARS-CoV-2 using standard LED lighting containing spectral wavelengths from 400 to 420 nm. Standard LED lights were used to irradiate samples over a course of 24 h while sampling at 4, 8, 12 and 24 h (done in independent triplicates). Blue bars indicate treated samples and red bars correspond to the untreated equivalent that was left at the biosafety cabinet under the same conditions while not subjected to disinfecting irradiation. Data shown as $PFUml^{-1}$ in triplicate assessed by plaque assay.

a different lipid-enveloped RNA virus was conducted by using influenza A Puerto Rico (A/H1N1/PR8-Mount Sinai) virus strain. Irradiation with a high dose of 0.6 mW cm^{-2} suggested a time dependent reduction of infectious titers as calculated by the 0.1619 log_{10}, 0.5609 log_{10}, and 1.6115 log_{10} (66 times) reductions at 1, 2, 4 and 8 h respectively (**Figure 3**A). And the reduction of plaques was apparent (**Figure 3**B). The stability of IAV virus at room temperature for a period of 8 h was found to be the negligible in untreated IAV spiked PBS samples (**Figure 3**A).

Encephalomyocarditis Virus (EMCV) as a Model Non-enveloped Virus Indicates Reduced Susceptibility to 405 nm Inactivation in the Absence of Photosensitizers

In order to better understand the effect of the lipid-envelope in viral inactivation by 405 nm irradiation, we used a non-lipid enveloped RNA virus derived from the Picornaviridae family. EMCV virus was irradiated at a high dose of 0.6 mW cm^{-2} similar to SARS-CoV-2 and IAV.

In this case however, a total reduction of 0.0969 (approximately 2 times) in comparison to the untreated after 8 h of irradiation was observed (**Figure 4**A,B) indicating a lower rate of inactivation (despite identical dosing) in contrast to the lipid-enveloped RNA viruses tested in this study. The plaque reduction at 8 h did not indicate the same dramatic reduction as observed with the latter studies.

Disinfection Potential of Standard LED Lighting Containing Spectral Wavelengths from 400 to 420 nm

As shown in **Figure 1**D, standard LED lighting (without the specific addition of 405 nm light) has a small but measurable amount of disinfecting light (0.006 mW cm^{-2}) in the 400 nm to 420 nm range. To quantify the disinfecting effect of this light, irradiations were performed for 4 h, 8 h, 12 h, and 24 h. A reduction of 0.7 log was observed by 4 h in comparison to the controls. By 24 h, a total of 1.7 log was observed using a standard LED light (**Figure 5**).

Discussion

The ongoing SARS-CoV-2 pandemic has affected day-to-day functions in the entire world, raising concerns not only with regards to therapeutics but also in the context of virus survivorship and decontamination [36]. Taking into consideration the rapid spread of SARS-CoV-2 from person to person by droplets, aerosols, and fomites, whole-room disinfection systems can be viewed as a supplement to best practices for interrupting transmission of the virus.

Given the ongoing COVID-19 pandemic, we wanted to explore the impact of 405 nm enriched visible light technology on inactivation of respiratory pathogens such as SARS-CoV-2 and influenza A virus. Without the use of exogenous photosensitizers, we were able to show that irradiation with low intensity (0.035 mW cm^{-2}) visible light yielded a reduction of log_{10} 0.3288 inactivation after 4 h (0.5 J/cm^2) and a total log_{10} 1.0325 inactivation of SARS-CoV-2 after 24 h (3.02 J/cm^2). A slightly higher dose (0.076 mW cm^{-2}) resulted in log_{10} 1.5393 reduction after 24 h (6.56 J/cm^2) while an irradiation dose of 0.150 mW cm^{-2} showed a reduction log_{10} 2.0056 after 24 h (12.96 J/cm^2) of irradiation. Finally, increasing the dose to 0.6 mW cm^{-2} yielded log_{10} 2.3010 reduction only after 8 h (17.28 J/cm^2), indicating a both time and dose dependent inactivation of infectious viruses.

The irradiations using standard LED lighting raise some interesting questions for further discussion. With nearly 6× the amount of disinfecting light as compared to traditional fluorescent lighting but 1/6th the lowest amount of 405 nm used in the study; it is conceivable that a reduction could be observed. The magnitude of this effect at less than 24 h was larger than expected based on other irradiations performed in this study (**Figure 5**). These results at 24 h were largely consistent with other irradiation levels and reinforce the general observation of a 405 nm dose-dependent effect. The intermediate irradiation levels (4 h, 8 h, and 12 h) were generally larger than expected even when accounting for experimental uncertainty.

A similar effect was observed by Bache, et al. in whole-room bacterial reduction studies [37]. They saw a disinfecting effect for irradiance values as low as 0.0023 mW cm^{-2}. This effect was shown to be uncorrelated to the level of irradiance used suggesting that the mere abundance of 405 nm light can initiate the oxidizing chemical reaction. Nevertheless, our results clearly show a dose-dependent effect. One possible explanation for this observation is that the lower irradiance levels expose different responses by specific organisms within a population based on the individual biology of that organism. Clearly, these results suggest that additional factors may be at work and warrant further investigation.

We selected conventional plaque assays as the read out to specifically estimate infectious virus titers upon disinfection. Methods based in the quantification of viral RNA via PCR based techniques might be misleading as they detect viral RNA from both infectious and noninfectious virions.

SARS-CoV-2 is a lipid-enveloped virus composed of a ssRNA genome and our data indicates its susceptibility to visible light mediated inactivation. To further confirm these observations, we used influenza A virus. which is another human respiratory virus with a lipid envelope and a segmented-RNA genome. Upon irradiating for 1 h at 0.6 mW cm^{-2} (2.16 J/cm^2), we observed a total reduction of log_{10} 0.1619 for the influenza A virus compared to the reduction of log_{10} 0.4150 for SARS-CoV-2 under the same conditions. While both viruses have lipid envelopes, there is clearly a difference here that will require further study. One possible explanation is the difference in the virion size creating a physically smaller cross-section for absorption. (IAV ≈ 120 nm and SARS-CoV-2 ≈ 200 nm) [38,39]. Nevertheless, both viruses were largely inactivated after 8 h achieving more 1.5 $\log_{10}$ reduction. Intriguingly, it was observed that both RNA viruses were able to remain stable at room temperature for at least 24 h, indicating minimal decay which is consistent with previous studies [36,40]. We next irradiated a non-enveloped RNA virus, EMCV. Previous results for visible light against non-enveloped viruses demonstrated the need for external photosensitizers such as artificial saliva, blood, feces, etc [30,36]. Without a porphyrin containing medium, we expected little to no inactivation when this virus was irradiated with visible light. For these measurements, we used the highest available irradiance of 0.6 mW cm^{-2}. As anticipated, we observed only a $\log_{10}$ 0.0969 reduction after 8 h, however, this appears to be with the statistical precision of the measurement based on the results obtained from shorter irradiations (1, 2, and 4 h). For comparison, a study involving the M13-bacteriophage virus (a non-enveloped virus) showed a 3-Log reduction using an irradiance of 50 mW cm^{-2} (almost 100 times greater than the highest irradiance used in this study) for 10 h at 425 nm further supporting the idea that non-enveloped viruses may require higher doses of visible light [41].

Our study was conducted using a neutral liquid media composed of PBS without any photosensitizers and we were able to show that visible light can indeed inactivate lipid-enveloped viruses, differing from the theory that states that photosensitizers are a requirement for inactivation. While these results provide insight into the basic science involved, they were performed within the context of the applied science needed to show the potential impact of this technology upon the current COVID-19 pandemic. By using safe, commercially practical irradiance levels, our results are more directly translatable to occupied rooms in the clinical environment.

Other studies which used visible light-based irradiation have shown similar results in the absence of photo-sensitizers, indicating the possibility of an alternative inactivation mechanism [23,25,30]. Studies have proposed two theories for this observation primarily due to non-405 nm wavelengths emitted by the source: (1) some amount of 420–430 nm emitted from the source is contributing to the viral inactivation [42], and (2) the presence of UV-A (390 nm) within the source. This wavelength is known to create oxidative stress upon viral capsids [43].

Longer wavelengths, such as 420–430 nm, have shown inactivation of the murine leukemia virus (MRV-A)[42]. While this is an intriguing study, it used a broad-spectrum lamp with optical filters to selectively identify the spectrum primarily responsible with their results. Unfortunately, they did not quantify the amount of light (using radiometric units) within the spectrum of interest used to irradiate the virus. While the transmission profile of the filters used was provided, it does not consider the spectral composition of the source itself making any direct quantitative comparison between our studies impossible. It is interesting to note that they did observe viral inactivation in their controls from wavelengths less than 420 nm confirming the qualitative findings of our study without confirming the specific use of 405 nm. This suggests that the viral inactivation is a likely a broad response ($>$ 20 nm) with relative contributions unique to the chemistry of each organism. They also considered much longer exposures (≈ 7 days) and much higher illuminance ($>$ 200 lx) than that used in our study although this is again difficult to compare given the lack of radiometric quantification of their light source. It is important to note that the control samples used in our study were exposed to the same overhead (non-405 nm) lights as the irradiated samples and our results are the observed difference between the two demonstrating the contribution from 405 nm over and above that potentially from 420 nm to 430 nm. Future experiments can further quantify the potential effect.

The other theory, potential UV-A irradiation, was historically applied to lamp-based sources with broad spectral ($>$ 100 nm) outputs. Again, the use of LED technology addresses this question as the peak irradiance at 390 nm of the device used in this study was $<$ 1% of its peak irradiance at 405 nm without the need for any additional filtration. Future experiments can further quantify the potential effect.

Another consideration to be addressed is thermal heating of the virus by the LED source. Tsen and Achilefu used a pulsed laser method at 425 nm [44] with ≈ 100 mW cm^{-2} average power density for $<$ 2 h while simultaneously measuring the sample temperature with a thermocouple. They detected less than a 2 °C demonstrating minimal temperature impact even under a power density nearly 9 orders of magnitude larger than that used in this study. This was confirmed by our thermocouple measurements as stated earlier. Nazari et al. used an 805 nm source with an average power density of $>$ 0.3 W/cm^2 for 10 s, nearly 1000 times that used in this study [45]. While the total energy delivered was more comparable to that used in our study, they did not make explicit temperature measurements, their analysis ruled out any potential thermal effects.

One possible explanation for the observed differences between the enveloped and non-enveloped organisms is absorption of the 405 nm light by the lipid envelope itself. This could, in turn, lead to the creation of reactive oxygen species (causing an oxidative effect) or simply destruction of the envelope leading to a denaturing of the organism. This question could serve as the basis for a range of future studies.

The results obtained suggest that the performance of visible light against SARS-CoV-2 is similar to other organisms commonly found in the environment such as S. aureus. Previous studies have shown that the visible light irradiance levels used in this study (0.035 mW cm^{-2} to 0.6 mW cm^{-2}) reduce bacteria levels in occupied rooms and improve outcomes for surgical procedures. It is therefore reasonable to conclude that visible light might be an effective disinfectant against SARS-CoV-2. More importantly, this disinfection can operate continuously as it is safe for humans based upon the exposure guidelines in IEC 62471 [46]. This means that once it has been in use for a period of time, the environment will be cleaner and safer at all future times including when it is occupied by humans.

One limitation of this study is that the inactivation assays were performed in static liquid media as opposed to aerosolized droplets. While the use of visible light in air disinfection has been briefly studied where it was shown that its effectiveness increased approximately fourfold [47], further studies involving dynamic aerosolization are needed to better understand the true potential of visible light mediated viral inactivation. In any case, our study shows the increased susceptibility of enveloped respiratory viral pathogens to 405 nm mediated inactivation in the absence of photosensitizers. The irradiances used in this study are very low and might be easily applied to disinfect occupied areas safely and continuously within hospitals, schools, restaurants, offices and other locations. Of particular interest is the potential for standard LED lighting to play a role in reducing the presence of SARS-CoV-2 in the environment.

Conclusions

We have demonstrated the basic science of inactivation of enveloped viruses such as SARS-CoV-2 and Influenza-A using 405 nm visible light within the context of the applied science required for this technology to have an impact upon the current COVID-19 pandemic. Without the need for exogenous photosensitizers and by using safe, commercially practical irradiance levels, our results can be easily translated to the clinical environment.

Future Efforts

Future work should focus on explaining the difference between the enveloped and non-enveloped results. This may include transmission electron microscopy (TEM), hemagglutination assay (HA), or other methods focusing on the potential role that a mediated reaction (due to the envelope itself) might play. The size of the virion particle may play a role in photoelectric absorption and could be studied for different viral species. We acknowledge that while unlikely, other wavelengths of visible light, beyond 400–420 nm may play a role in the inactivation process and future studies should explore this possibility as well. Finally, the inactivation kinetics of low irradiances could add valuable insight into clinical applications of this technology. ■

Acknowledgements
We thank Kenall Manufacturing for supplying the M4DLIC6 fixture and test rig used in this study. We thank Randy Albrecht for support with the BSL3 facility and procedures at the ISMMS, and Richard Cadagan for technical assistance. This research was partly funded by CRIP (Center for Research for Influenza Pathogenesis), a NIAID supported Center of Excellence for Influenza Research and Surveillance (CEIRS, contract # HHSN272201400008C); by the generous support of the JPB Foundation, the Open Philanthropy Project (research grant 2020-215611 (5384)) and anonymous donors to AG-S, and by a research contract from Kenall Manufacturing to the AG-S lab.

Author Contributions
R.R., C.Y. and A.G.S. conceptualized the project. R.R., S.J., L.M. and M.S. performed experiments and compiled the manuscript. All authors reviewed the manuscript.

Competing Interests
The García-Sastre Laboratory has received research support from Pfizer, Senhwa Biosciences, 7Hills Pharma, Avimex, Blade Therapeutics, Dynavax, ImmunityBio, Nanocomposix and Kenall Manufacturing. Adolfo García-Sastre has consulting agreements for the following companies involving cash and/or stock: Vivaldi Biosciences, Pagoda, Contrafect, 7Hills Pharma, Avimex, Vaxalto, Accurius, Pfizer and Esperovax. RR, CY and AGS have filed for a provisional patent based upon these results.

Additional Information
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Author: Adolfo GARCIA-SASTRE, Ph.D.
Dr. García-Sastre is Professor in the Department of Microbiology and Director of the Global Health and Emerging Pathogens Institute of Icahn School of Medicine at Mount Sinai in New York. For the past 25 years, his research interest has been focused on the molecular biology of influenza viruses and several other negative strand RNA viruses. During his post-doctoral training in the early 1990s, he developed, for the first time, novel strategies for expression of foreign antigens by a negative strand RNA virus, influenza virus. He has made major contributions to the influenza virus field, including 1) the development of reverse genetics techniques allowing the generation of recombinant influenza viruses from plasmid DNA, (studies in collaboration with Dr. Palese); 2) the generation and evaluation of negative strand RNA virus vectors as potential vaccine candidates against different infectious diseases, including malaria and AIDS, and 3) the identification of the biological role of the non-structural protein NS1 of influenza virus during infection: the inhibition of the type I interferon (IFN) system. His studies provided the first description and molecular analysis of a viral-encoded IFN antagonist among negative strand RNA viruses. These studies led to the generation of attenuated influenza viruses containing defined mutations in their IFN antagonist protein that might prove to be optimal live vaccines against influenza. His research has resulted in more than 480 scientific publications and reviews. Dr. García-Sastre is the director of the Center for Research on Influenza Pathogenesis (CRIP), one of the five NIAID funded Centers of Excellence for Influenza Research and Surveillance. He was among the first members of the Vaccine Study Section and member of the Virology B Study Section of NIH. In addition, he has served for 5 years as Editor of Journal of Experimental Medicine, is Editor of PLoS Pathogens, Journal of Virology and Virus Research, and member of the Editorial Board of Virology, Vaccine, NPJ Vaccines and Influenza and Other Respiratory Diseases. He is a member of the scientific advisory board of Keystone Symposia. He has been a co-organizer of the international course on Viral Vectors (2001), held in Heidelberg, Germany, sponsored by Federation of European Biochemical Societies (FEBS), and of the first Research Conference on Orthomyxoviruses in 2001, held in Teixel, The Netherlands, sponsored by the European Scientific Working Group on Influenza (ESWI). He has also been a co-organizing of the 7th International Society for Vaccines meeting in 2013, and of Keystone Meetings in 2014 on Respiratory Virus Pathogenesis and in 2017 on Interferons. His publication in Science on the reconstruction and characterization of the pandemic influenza virus of 1918 has been awarded with the distinction of the paper of the year 2005 by Lancet. In 2005, he became a Fellow of the American Academy of Microbiology, and in 2009, he received the Beijerink Professorship from the National Academy of Sciences of the Netherlands. In 2011, he has been elected President of the International Society for Vaccines, for 2014 and 2015. In 2017, he has been elected a fellow of the Royal Academy of Pharmacy in Spain.

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Dr. Yahnke received his B.S. in Engineering Physics from the Illinois Institute of Technology and his Ph.D. in Physics from Northwestern University. He joined Kenall in 2013 bringing over 25 years of photonics and healthcare experience in a range of fields related to defense, telecommunications, radiation oncology, medical imaging, analytical instruments, and surgical lighting to Kenall. As one of the inventors of Indigo-Clean, Dr. Yahnke has led its development and introduction into healthcare facilities across the US. Widely regarded as the industry expert on visible light disinfection, he has authored numerous articles on it and led numerous studies demonstrating Indigo-Clean's ability to reduce bacteria and infections in clinical settings. His current research interests are focused on the transmission of bacteria in the perioperative setting, its impact on various surgical modalities, and the use of visible light disinfection in combating SARS-CoV-2 transmission. Most recently, Dr. Yahnke was part of the team whose ground breaking research into SARS-CoV-2 disinfection using visible light was published in Nature-Scientific Reports.

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Fundamentals of Disinfection Device Development

Dominik KÖCK, MSc, Product Manager at Würth Elektronik eiSos

The coronavirus pandemic has made disinfection a ubiquitous topic. In addition to chemical methods, ultraviolet radiation of particular wavelengths can be used for sterilization. For example, UV LEDs that emit radiation in the UV-C range (100–280 nm), open up a wide range of possibilities in the design of disinfection devices. So, what needs to be considered?

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The disinfecting effect of UV light has been known since 1877 and already attracted great interest in the fight against diseases such as tuberculosis. In the past, low-pressure mercury vapor discharge lamps were used because they emit at the germicidal wavelength of 254 nm and have relatively high radiation powers. To this day, they are often the most economical solution for large-area disinfection. However, UV-C LEDs offer several other advantages. They do not contain hazardous substances such as mercury; they do not have long warm-up times; and they are also robust against frequent switching on and off. Vibration and shock resistance as well as small size are further advantages. The Covid-19 pandemic has given a further boost to the research and commercial availability of UV-C LEDs such that the use of UV-C LEDs is now feasible in many applications.

Basics

UV-C disinfection is based on the fact that UV-C radiation damages DNA and inhibits the proliferation of bacterial, fungal, plant and animal cells. In a similar mechanism, UV light damages the RNA of viruses, which renders them inactive. The more damage caused to the RNA, the less the virus can infect other organisms. To achieve a good sterilization result, a combination of the right wavelength and a high amount of radiation is needed. **Figure 1** shows the spectrum of a UV-C LED compared to the wavelength-dependent RNA-damaging effect.

Of course, the optimum solution would be an LED with a peak wavelength that corresponds exactly to the wavelength with the maximum RNA damage. However, **Figure 2** shows that LEDs with these wavelengths currently still have a lower efficiency (Wall-Plug-Efficiency – WPE) and thus lower optical power and a less effective sterilization effect. Würth Elektronik's UV-C LEDs [1] combine a near optimal wavelength of 275 nm as well as a high optical power and are therefore well suited for sterilization.

Dose

To quantify how well disinfection works, the term 'log reduction' is used. A log reduction of n means that only 10^{-n} of the previous germs have survived. For example, 1 log reduction means that only $10^{-1} = 10\%$ of the germs survived. That means 90% of the germs were inactivated. At 4 log reduction, $10^{-4} = 0.01\%$ survived, i.e. 99.99% were inactivated. To achieve this amount of germ inactivation, a certain amount of UV-C light has to be absorbed by the germs. This amount is called the dose (irradiance $\times$ exposure time) and is measured in J/m^2. For a 1 log reduction, the dose $D90$ is the amount of UV-C light needed to inactivate 90% of the germs (**Table 1**). For a 4 log reduction, the dose $D99.99$ is needed to inactivate 99.99% of the germs. To estimate the value for the $D99.99$ dose, one can simply multiply the $D90$ dose by a factor of 4.

Several studies have investigated the $D90$ dose for viruses, other germs and specifically for coronavirus. Due to different experimental setups, this dose varies greatly between the different research groups. The values given in **Table 1** are individual results or median values from individual research groups. Although these studies were conducted with low-pressure UV-C lamps, a similar $D90$ dose can be assumed for a 275 nm LED, since the damaging effect is similar at 254 nm, emitted by low-pressure UV-C lamps (compare **Figure 2**).

In a German water disinfection guideline, a value of 400 J/m^2 is required for disinfection with UV-C low-pressure lamps. This value is higher than the $D90$ dose for most typical germs and can be considered a guideline value for the design of disinfection systems.

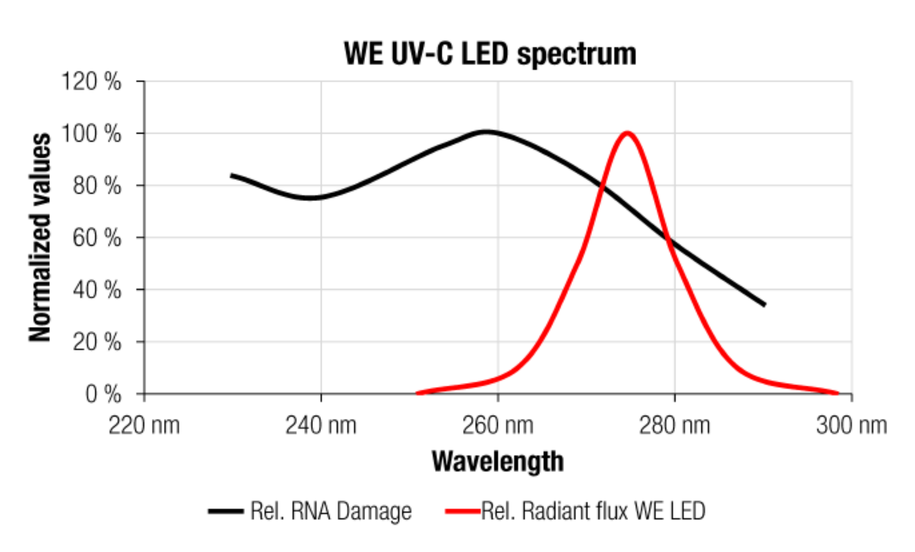

Figure 1: Spectrum of a UV-C LED compared to the RNA damaging effect.

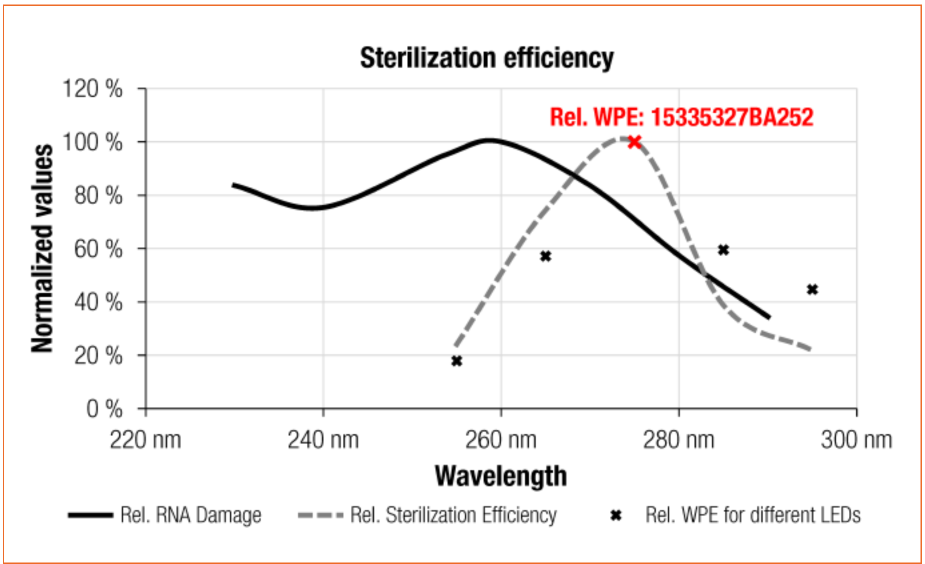

Figure 2: The sterilization efficiency (gray) as the product of RNA damage (black) and WPE (crosses) is shown as a function of wavelength. A good sterilization efficiency can be achieved with the 275 nm LEDs.

Microorganism	Pathogen information	D90 Dose (J/m^2)	Type of lamp
Virus			
Corona virus	Coronavirus like SARS-CoV-2	37	LP
Hepatitis virus	Causes hepatitis	40	LP
Influenza	Causes flu	20	LP
Adeno virus	Causes colds	390	LP
Bacteria			
Salmonella typhimurium	Causes food poisoning	39	LP
Escherichia coli	Causes food poisoning	43 (275 nm)	LED
		41 (254 nm)	LP
Legionella pneumophila	May be present in water pipes	17	LP
Fungi			
Aspergillus niger	Black mold formation	1160	LP

Table 1: Overview of a few D90 doses.

However, as the disinfection result is dependent on many conditions such as surface properties or absorption of UV-C radiation, studies must be carried out for each system to prove reliable disinfection.

When designing disinfection applications, it is important to understand how a certain dose can be achieved. For this, a few figures need to be understood:

- **Radiant flux:** The radiant flux is the total optical power output of the LED and is measured in units of [W]. This is a value that can be read from the datasheet.
- **Irradiance:** Irradiance is the amount of radiant flux received by a surface per irradiated area and is expressed in units of [W/m^2]. This irradiance can be simulated or measured for different configurations of LEDs.
- **Exposure time:** The time for which a surface is exposed to radiation.
- **Radiant exposure:** The radiant exposure or fluence is the amount of energy received by a surface. It is calculated from irradiance × exposure time.
- **Dose DXX:** Dose is the amount of energy per surface required to achieve a certain percentage of disinfection (XX % inactivation). To achieve a certain level of disinfection, the surface must be irradiated until it has accumulated a radiant exposure that equals the desired dose.

This means that the time needed to achieve a desired disinfection result can be estimated by knowing the desired dose and the irradiance of the system.

Example Simulation

In **Figure 3** the irradiation distribution for different heights of a PCB with 9 WL-SUMW 15335327BA252 LEDs is shown. With increasing height, the irradiated area becomes larger, but the maximum irradiance decreases. As a result, the exposure time required to obtain a certain dose increases with the square of the distance (required exposure time $\propto$ distance^2), as shown in the inset for a dose of 37 J/m^2 and detailed in **Figure 3**, **Table 2**.

This calculation gives an important indication of the required disinfection times before the necessary product tests.

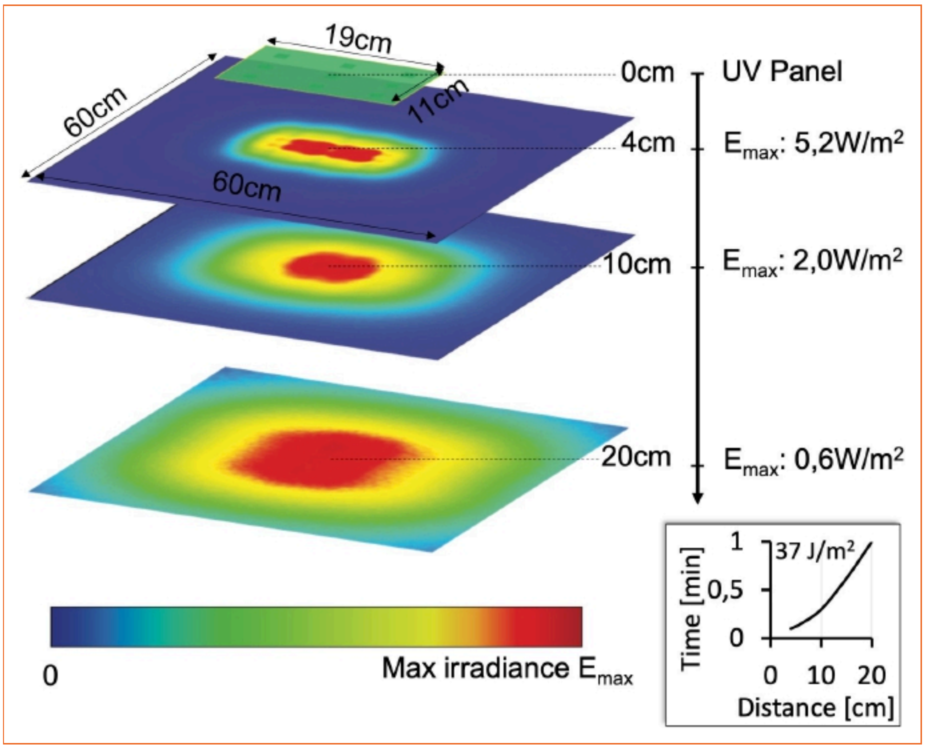

Figure 3: The irradiance distribution for different heights of a panel with nine LEDs from Würth Elektronik (WL-SUMW 15335327BA252).

Distance	Irradiance	Required exposure time for:	
		Dosis 37 (J/m²)	Dosis 400 J/m²)
4 cm	5.2 W/m²	0.1 min	1.3 min
10 cm	2.0 W/m²	0.3 min	3.3 min
20 cm	0.6 W/m²	1.0 min	11.1 min

Table 2: Required exposure times for the example UV panel to achieve a certain dose, depending on the distance.

Safety

UV light can cause degradation in polymers, such as change of color, reduction of elasticity and strength that might result in cracks under stress. This should be considered when developing applications and selecting materials. But it is even more important to avoid exposure to eye and skin tissue. In nature, UV-C radiation is blocked by the ozone layer and does not reach the earth's surface. For this reason, living organisms on earth have not developed repair mechanisms for damage caused by UV-C light.

Figure 4: UV warning symbol according to IEC 60417-6040.

This is why UV-C is so effective in killing germs, but also why it is so dangerous for humans and animals. It is particularly dangerous to our eyes and skin and can cause skin damage even long after exposure.

According to Directive 2006/25/EC, the maximum permissible dose per eight-hour working day must not exceed 30 J/m^2. For continuous exposure, this means that the irradiance should not exceed 0.001 W/m^2.
Appropriate personal protective equipment or shielding must be used to ensure product safety. The following example gives an idea of what shielding requirements could look like.

Example Calculation for Shielding Materials

For the example UV panel shown above, the maximum irradiance at a distance of 20 cm is 0.6 W/m^2. To get below the maximum allowable irradiance of 0.001 W/m^2, a shielding must have a transmission of less than $\approx 10^{-3}$, assuming long-term exposure. However, it is strongly recommended to reduce the transmission of the shielding material even further, as the damage from UV-C radiation is cumulative over a long period of time. In addition, it should be noted that the irradiance is strongly dependent on the distance to the UV-C source.
If in our example the distance between UV panel and skin/eyes is 4 cm, the transmission of a shielding material should already be less than $\approx 10^{-4}$. At a distance of 1 cm, the transmission should already be less than $\approx 10^{-5}$.
If too much UV-C light leaves the application, such as with hand lamps, all persons potentially exposed to the radiation must be properly trained and wear adequate personal protective equipment such as face shields, gloves and protective clothing.

Summary

Devices with UV-C LEDs for disinfection purposes will play an increasingly important role not only in the current pandemic situation but also in the future, for example in coping with healthcare issues such as multi-resistant germs. UV-C LEDs will also be increasingly in demand for general germ reduction in air filtration systems, in water supplies and in the food industry. The topics touched on have made it clear that the development of UV-C applications require the greatest care and extensive testing. If RayFiles are available, as with Würth Elektronik's LEDs, the effort of application design can be reduced by simulating the irradiance before building a prototype. ■

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After graduating from the University of Würzburg 2019, including a stay at the University of British Columbia, Canada, Dominik started as Product Manager in the Optoelectronic department of the Würth Elektronik eiSos GmbH & Co. KG. In his studies, he focused on semiconductor physics, plasmonics and integrated quantum photonics. During his studies, he gained experience in the production of a leading semiconductor laser company. Today he is involved as a product manager with UV-LEDs in Würth Elektronik's area of opto-electronics.

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How to Use LTspice to Produce Bode Plots for LED Drivers

Keith SZOLUSHA, Applications Director and Brandon NGHE,
Applications Engineer at Analog Devices

Closed-loop gain and phase plots are well-worn tools used to determine the stability of the control loop in switching regulators. Gain and phase measurements, when done properly, require access to, and familiarity with, fancy network analyzers. The measurements involve breaking the control loop, injecting noise, and measuring the resulting gain and phase over a frequency sweep (see Figure 1). This practice of measuring the control loop is rarely applied to LED drivers. LED driver control loop phase and gain measurements require a different approach (Figure 1) — a deviation from the typical resistive-divider-path-to-GND voltage regulator injection and measurement point. In both cases, benchtop control loop phase and gain measurements are the best way to guarantee stability, but not every engineer has the required equipment and access to an experienced factory apps team at their fingertips. What do these engineers do?

One option is to build the LED driver and see how it responds to transients. Transient response observation requires the application board and more common benchtop equipment. The results of transient analysis lack the Bode plot's frequency-based gain and phase numbers – which can be used to guarantee stability – but they can act as a telltale for general control loop stability and speed.

Large signal transients can be used to check absolute deviation and system response time. The shape of the transient disturbance indicates the phase or gain margin and thus can be used to understand general loop stability. For instance, a critically damped response might indicate 45° to 60° phase margin. Or, a large spike during the transient can indicate the need for more C_{OUT} or a faster loop. A long settling time can indicate the need to speed up the bandwidth (and crossover frequency) of the loop. These relatively easy system checks enable on-the-fly characterization of a switching regulator's control loop, but gain and phase Bode plots are required for deeper analysis.

LTspice® simulation can be used to generate both switching regulator output transients and Bode plots before circuits are assembled or fabricated. This can help to get a rough idea of control loop stability – a starting point for compensation component choices and output capacitor sizing. The process of using LTspice based on Middlebrook's original recommendation in 1975 is well documented (see "LTspice: Basic Steps in Generating a Bode Plot of SMPS" [1]). The actual signal injection location laid out in Middlebrook's method is not commonly used these days but has been adjusted over the years, resulting in the commonly used injection location shown in **Figure 1**a.

Furthermore, LED drivers, with high-side sense resistors and complicated AC resistance LED loads, should have a different injection point than either today's injection point or Middlebrook's original recommendation in the feedback path, one not previously demonstrated in LTspice. The method presented here shows how to generate LED driver current-sense feedback loop Bode plots in LTspice, and in the lab.

Producing Control Loop Bode Plots

Standard switching regulator control loop Bode plots yield three critical measurements, which can be used to determine stability and speed:

- Phase margin
- Crossover frequency (bandwidth)
- Gain margin

It is generally accepted that 45° to 60° of phase margin is required for a stable system, and that –10 dB gain margin is required for guaranteed loop stability. The crossover frequency relates to general loop speed. **Figure 1** shows the setup for making these measurements using a network analyzer.

LTspice simulation can be used to create a similar injection and measurement in the control loop for an LED. **Figure 2** shows an LED driver (LT3950) with an ideal sine wave of given frequency (f) injected directly into the feedback path on the negative sense line (ISN). Measurement points A, B, and C are used to calculate the gain (dB) and the phase (°) at the injection frequency (f). In order to graph the entire control loop Bode plot, this measurement must be repeated over a large frequency sweep, stopping at $f_{SW}/2$ (half of the switching frequency of the converter).

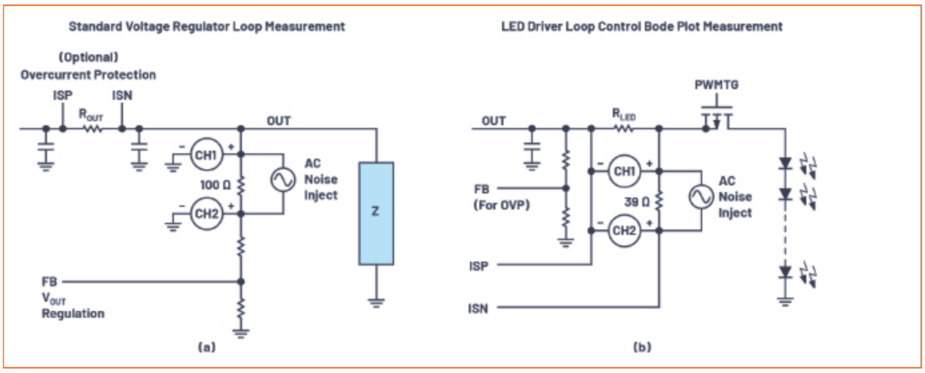


Figure 1: Switching regulator control loop Bode plot measurement with a network analyzer for **(a)** voltage regulator and **(b)** LED driver. To make the measurement, the control loop is broken and a sinusoidal perturbation pushes into a high impedance path, while the resulting control loop gain and phase is measured, enabling the designer to quantify the stability of the loop.

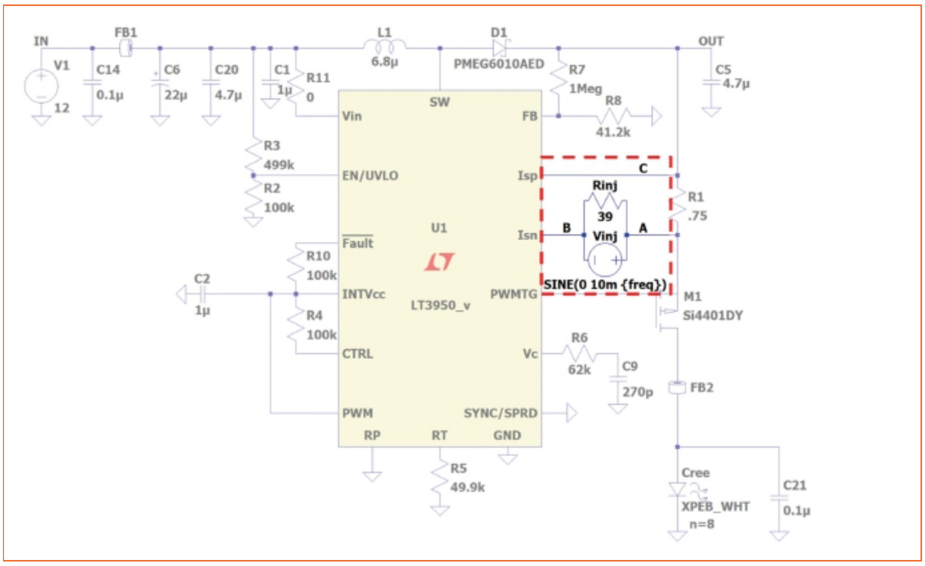
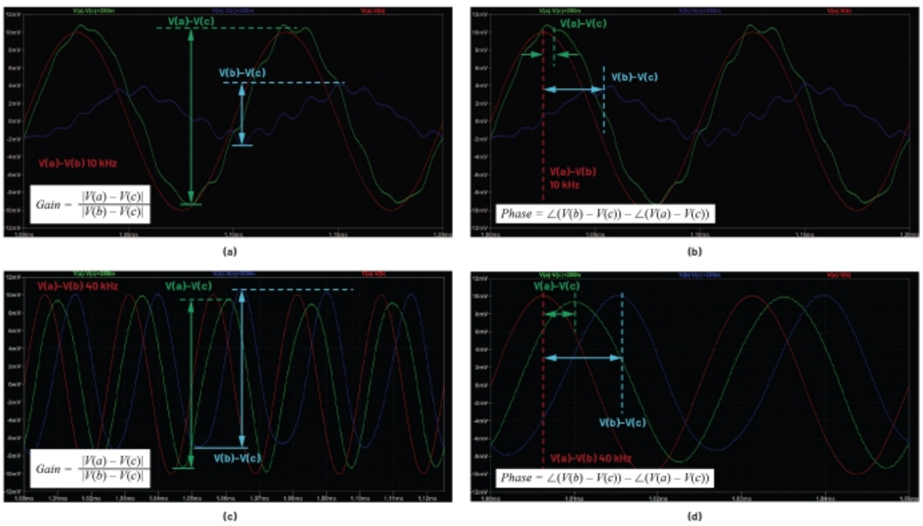


Figure 2: LT3950 DC2788A demonstration circuit LED driver LTspice model with control loop noise injection and measurement points.



(Waveforms A-C and B-C as well as Sine Wave A-B Demonstrated with Two Different Frequencies: 10 kHz and 40 kHz)

Figure 3: The measurement of points A, B, and C in Figure 2 determine the gain and phase of the control loop at the injection frequency (f). Different injection frequencies yield different gain and phase. Figures 3a and 3b show the gain and phase of $10\,\mathrm{kHz} \pm 10\,\mathrm{mV}$ AC injection. Figures 3c and 3d show the gain and phase of $40\,\mathrm{kHz} \pm 10\,\mathrm{mV}$ AC injection. A sweep of frequencies and the measurements of gain and phase between B-C and A-C are what form the closed-loop Bode plot.

The measurement of points A, B, and C in **Figure 2** determine the gain and phase of the control loop at the injection frequency (f). Different injection frequencies yield different gain and phase. For simplicity, and to see how this works, one can set the injection frequency and measure the gain and phase of A-C and B-C. This yields a single frequency point of the control loop Bode plot. **Figure 3**a and **Figure 3**b show the gain and phase of 10 kHz ±10 mV AC injection. **Figure 3**c and **Figure 3**d show the gain and phase of 40 kHz ±10 mV AC injection.

A sweep of frequencies and the measurement of gain and phase between B-C and A-C are what form the entire closed-loop Bode plot. As mentioned in the Abstract, this is typically accomplished on the bench using a fancy (that is, expensive) network analyzer. Such a sweep is also possible in LTspice, as shown in **Figure 4**. These results are confirmed by comparing them to the results of a benchtop test using a network analyzer (**Figure 8**).

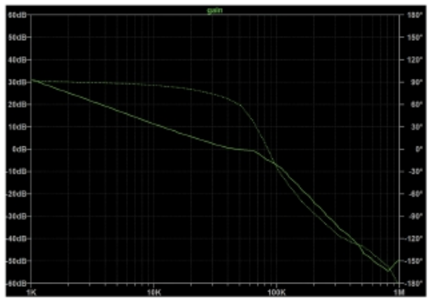


Figure 4: Bode plot measurements with the LT3950 in LTspice showing gain (solid line) and phase (dashed line).

Make Full Gain and Phase Sweeps and Plots in LTspice

To create a full Bode plot, a graphical sweep of gain and phase, in LTspice for the control loop, follow these steps.

Step 1: Create the AC Injection Source

In LTspice, insert the ± 10 mV AC injection voltage source and injection resistor and label nodes A, B, and C as shown in **Figure 2**. The AC voltage source value **SINE(0 10m [Freq])** sets the 10 mV peak and sweeps the frequency. The user can play with peak sine values between 1 mV and 20 mV. Keep in mind that sense voltage for many LED drivers is 250 mV and 100 mV. Higher injection noise can create LED current regulation errors.

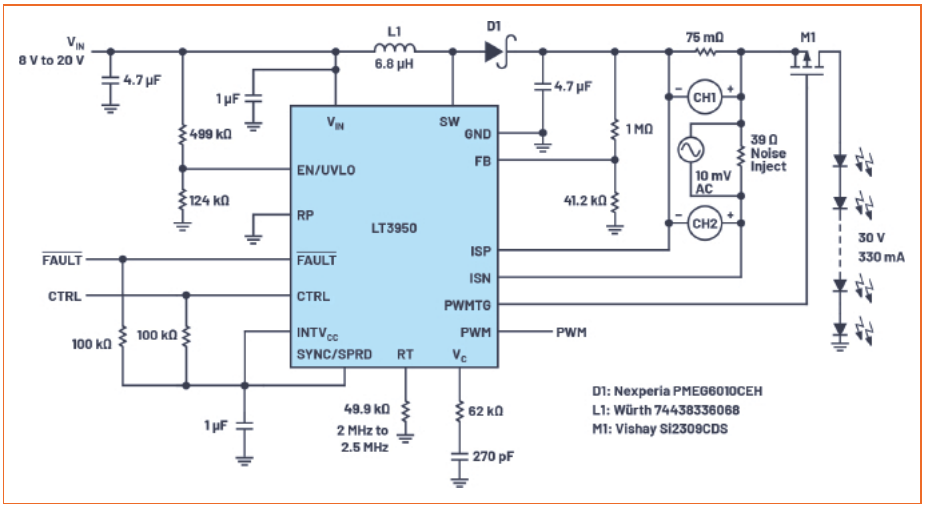


Figure 5: LED driver control loop Bode plot measurement setup using a network analyzer.

Figure 6: Venable System Model 5060A vintage network analyzer used for high-side floating noise injection and measurement of LED drivers.

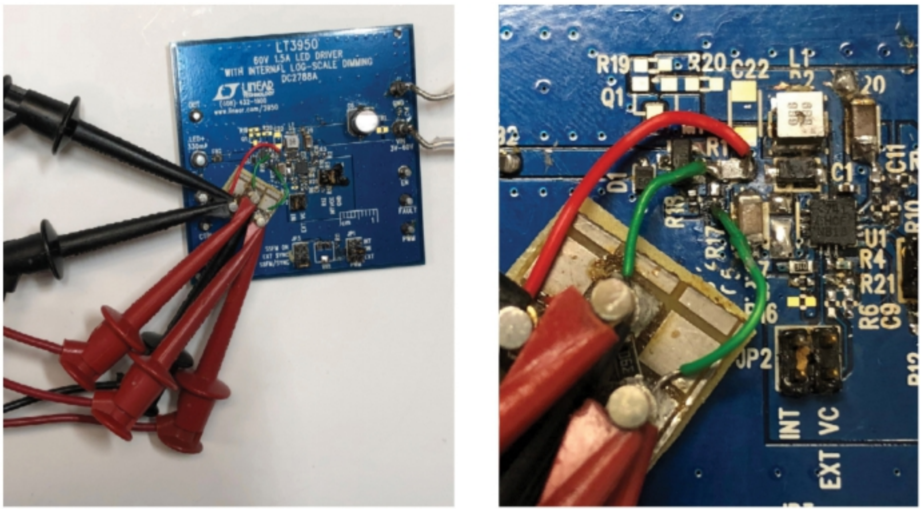


Figure 7: Noise injection and measurement points on the LT3950 LED driver.

Step 2: Add the Math

Insert the .measure statements on the schematic as .sp (SPICE) directives. These directives perform Fourier transforms and compute the complex open-loop gain and phase of the LED driver in dB and phase. Here are the directives:

- measure Aavg avg V(a)-V(c)
- measure Bavg avg V(b)-V(c)
- measure Are avg (V(a)-V(c)-Aavg)*cos(360*time*Freq)
- measure Aim avg -(V(a)-V(c)-Aavg)*sin(360*time*Freq)
- measure Bre avg (V(b)-V(c)-Bavg)*cos(360*time*Freq)
- measure Bim avg -(V(b)-V(c)-Bavg)*sin(360*time*Freq)
- measure GainMag param 20*log10(hypot(Are,Aim) / hypot(Bre,Bim))
- measure GainPhi param mod(atan2(Aim, Are) - atan2(Bim, Bre)+180,360)-180

Step 3: Set the Measurement Parameters

A few more small directives are needed. First, the circuit must be in a steady state of the simulation (past startup) in order to make proper measurements. Adjust the t0, or start time for the measurement, and stop time. The start time can be estimated or garnered by starting up the simulation and observing the start-up time. The stop time is chosen to be 10/freq, or 10 periods, after steady state is reached—reducing errors by averaging over 10 cycles for each frequency.
Here are the directives:

- .param t0=0.2m
- .tran 0 [t0+10/freq] [t0] startup
- .step oct param freq 1K 1M 3

Step 4: Set the Frequency Sample Step and Range

The .step command sets the frequency resolution and range over which to perform the analysis. In this example, the simulation runs from 1 kHz to 1 MHz using a resolution of three points per octave. Bode plot measurements are accurate up to fSW/2, so the upper frequency limit should be set to half of the switching frequency of the system. Obviously, more points improve resolution, but the simulation takes longer. Three points per octave is the low end of resolution, but running the simulation at minimum resolution can save some time. Nevertheless, looking at the overall design cycle picture, a 5-minute simulation is orders of magnitude faster than designing, assembling, and testing PCBs. With this in mind, you may want to just run at a higher resolution, such as five or more points per octave, to produce more complete and easier to view results.

Step 5: Run the Simulation

It seems straightforward, but LTspice requires multiple production steps to produce the Bode plot. The first step is Run the Simulation, which does not yield (yet) the plot, but instead shows normal scope voltage and current measurements. Follow the next steps to produce the Bode plots.

Step 6: Produce the Bode Plot

Open the SPICE Error Log by right-clicking the schematic window and choosing Plot .step'ed .meas data. Choose Visible Traces from the Plot Settings Menu and select Gain to plot the data. Optionally, measurement data can be exported by clicking File and selecting Export Data as Text to produce a CSV file of the Bode data.

Bode Plot Confirmation with a Network Analyzer—Beyond Simulation

Simulation of control loops is not as reliable as the real thing and should not be used for a complete guarantee of loop stability and margins. At some stage of the design process, the control loop should be verified in the lab using a network analyzer tool.

The Bode plots generated in LTspice can be compared to network analyzer Bode plot measurement results. Just like the simulation, the actual loop measurements are captured by injecting noise into the feedback loop and measuring and processing the A-B and A-C gain and phase. The measurement setup schematic and photo are shown in **Figure 5** through **Figure 7**.

LTspice simulation results (**Table 1**) show a strong correlation to network analyzer data, proving that LTspice is a useful tool in LED driver design—producing a rough baseline to aid the engineer in narrowing the range of component choices. The gain and phase at lower frequencies closely follow hardware, with a greater difference between simulation and hardware data at higher frequencies. This might represent the challenge of modeling high frequency poles, zeroes, parasitic inductances, capacitances, and equivalent series resistances.

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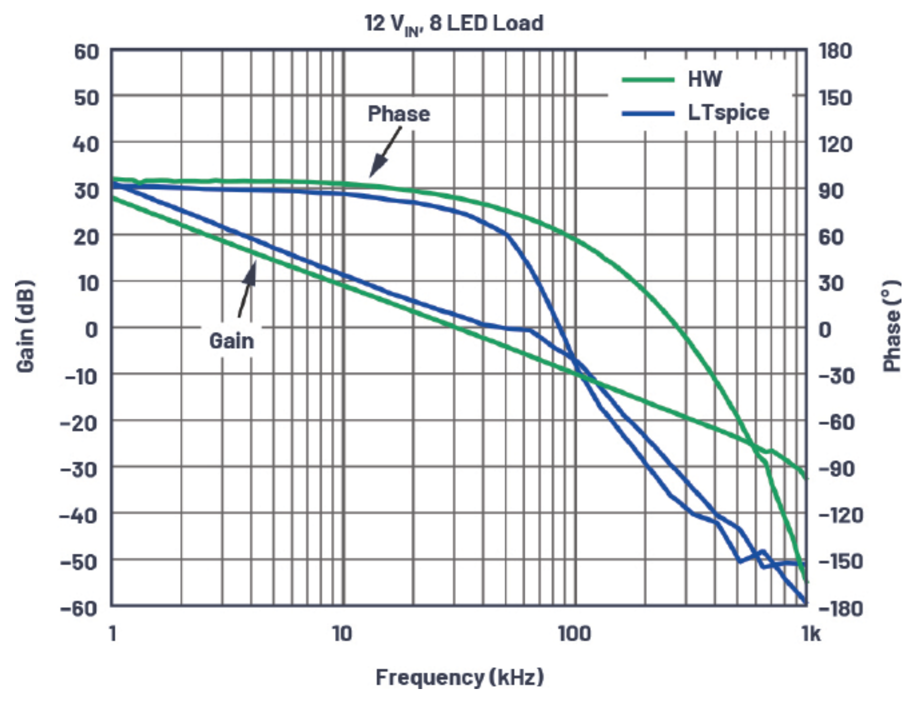

Figure 8: Bode plots for the LT3950 LED driver on a DC2788A demonstration circuit. The plots generated through LTspice simulation (blue line) have a strong correlation to those generated using a network analyzer (green line).

Test Setup	Crossover Frequency (kHz)	Gain Margin (dB)	Phase Margin (°)
Network analyzer, 8 V_{IN}	16.75	17.47	83.96
LTspice, 8 V_{IN}	15.8	13.79	71.23
Network analyzer, 12 V_{IN}	30.41	18.71	83.73
LTspice, 12 V_{IN}	47.36	5.04	62.29

Table 1: Bode Plot measurement data comparison of LTspice vs. network analyzer for the LT3950.

Conclusion

LTspice modeling can be used to measure control loop gain and phase, thus producing Bode plots for LED drivers. The accuracy of the LTspice simulation data is dependent on the accuracy of the SPICE models used, though carefully modeling each component to account for real-world behavior comes at the cost of increased simulation times. For the purpose of LED driver design, LTspice data is useful for relatively quickly narrowing the field of components and predicting general circuit behavior even without perfect component modeling. A working simulation helps guide the design engineer before transitioning to hardware implementation, saving overall design time. Once rough component choices have been made, measurements using a built board with a network analyzer can confirm or contrast the simulation results as a means of hardware validation during development. ■

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