LED professional

www.led-professional.com

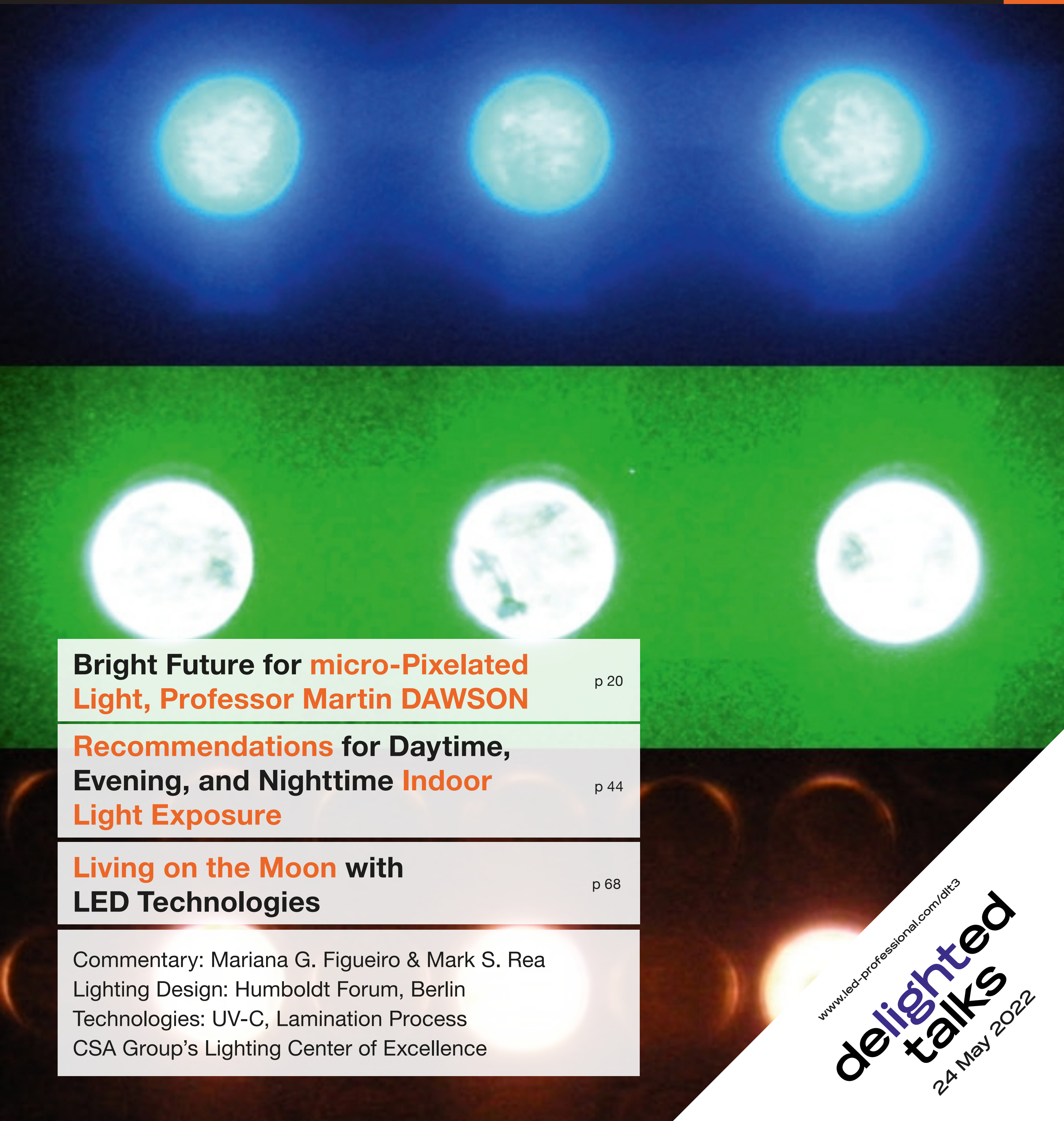
ISSN 1993-890X

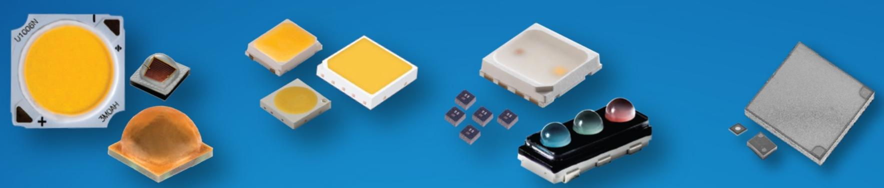
Review

LpR

The Global Information Hub for Lighting Technologies and Design

May/June 2022 | Issue 91





From micro-LEDs to Integrative Lighting

Putting together the 91st issue of the LED professional Review (LpR91) was both awe-inspiring and exciting. First of all, we were very grateful for the amazing interview with Professor Martin Dawson who pointed out the potential and opportunities of micro-LEDs. My thanks also go out to Professors Figeuiro and Rea for bringing the need for “circadian-effective lighting” to our attention. In addition, the report on the amount of light needed during the day, evening and nighttime, which presents scientifically supported limits for integrative lighting is well worth the read.

This issue also spans the angle between applications with articles about the project at the Humboldt Forum in Berlin, simulated life on the moon project, lighting technologies concerning UVC, and circuit protection. To top it off, the CSA Group presents the importance of excellent test environments for horticulture applications.

Currently, the topic of energy saving is coming back into focus. If you have any exceptional innovations on the topic of sustainability and energy saving via light, write to our editors at editors@led-professional.com.
We have also put together some ideas for you in the Lighting News.

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

Yours Sincerely,

Siegfried Luger

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

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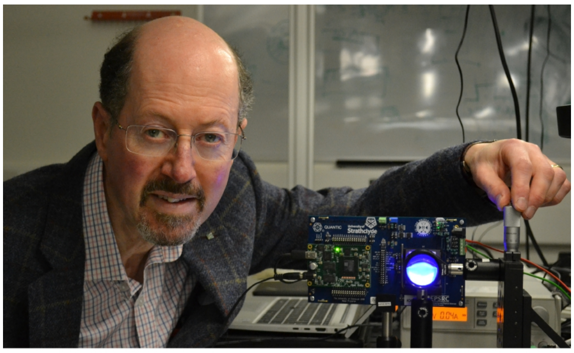

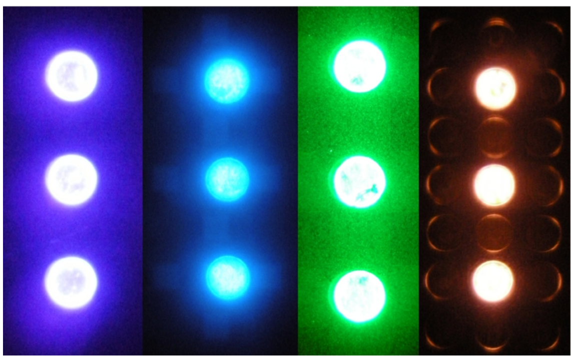


LpS DIGITAL
CONFERENCE
How to Address the Lighting Industry's Concerns Regarding Product Compliance Online
by Marion Ebel
Senior Policy Manager at LightingEurope
Brussels, Belgium

ADVERTISING INDEX

Mariana G. FIGUEIRO & Mark S. REA

Mariana FIGUEIRO is Professor of Population Health Science and Policy at the Icahn School of Medicine at Mount Sinai in New York and Director of the Light and Health Research Center (LHRC). In addition to performing basic research investigating the impact of light on physiology, Dr. Figueiro conducts field studies examining the impact of circadian-effective lighting in various populations.

Mark S. REA is a Professor in the Department of Population Health Science and Policy at the Icahn School of Medicine at Mount Sinai. He was formerly Professor of Architecture and Cognitive Sciences at the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute and served as LRC Director from 1988 to 2017.

Fear of Falling

Probably each one of us can remember the first time we tried to ride a bicycle. Many of us rebuffed our parents' encouragement to try "until we were ready." It was daunting because it was a completely novel endeavor and potentially dangerous. Of course, there was no way to get ready — we were just making excuses and putting off the inevitable. Finally, the time came, either through parental insistence or peer pressure, to get on the bicycle — and we promptly fell. After the Band-Aids and crying episodes, we eventually could ride without training wheels or parental support – but we *could ride*, and it was glorious. Our bicycle took us places we could never reach by foot, and we even formed new relationships with kids from other parts of town. Ultimately, we could not imagine the world without our bicycle — even though we occasionally fell. We still needed Band-Aids but, importantly, we didn't cry.

Circadian lighting (or perhaps a better term, *circadian-effective lighting*) is like learning to ride a bicycle. It's easy once you get the hang of it. And sure, you may need some Band-Aids and some help along the way from experts to get started. You might even cry, but eventually circadian lighting will take you places you have never been — demonstrably helping people sleep better and, as a result, helping them be more productive, happier, and healthier. You'll also meet some new people along the way — people who care more about the well-being of people than they do about vague terms like "lighting quality," whatever that may be.

> *"We are not ready yet [for circadian lighting]... but, dog walkers sleep better."*
>
> RUSSEL FOSTER, NEUROSCIENTIST

Russell Foster recently said that "We are not ready yet [for circadian lighting]." But he also stated that dog walkers sleep better. What is it that dog walkers get that makes them sleep better? Regular bright light in the morning. And this is consistent with what we have been advocating for a few years now. We need bright days and dim nights. We don't necessarily need complicated human-centric lighting systems that will cost us an arm and a leg.

> *"We are causing harm now by not providing circadian-effective lighting."*
>
> MARINA G. FIGUEIRO

No one can ride a bicycle the first time they try, but the only way to ride the bicycle is to begin riding the bicycle. The same thing is true for circadian lighting — the only way to do it right is to begin doing it, in the simplest way we can. One might say, however, that falling off the bicycle only hurts the rider, whereas failing at circadian lighting can harm the people we are trying to serve.

That's nonsense.

We are causing harm *now* by not providing circadian-effective lighting in the built environment, especially in spaces where people spend most of their days in dim light, such as nursing homes. Really, providing circadian-effective lighting is as simple as providing building occupants with brighter (in the eyes) days and dimmer nights. In fact, this is exactly what Foster said. Despite some unknowns, this simple, natural principle is what we have evolved to follow.

How we successfully follow that basic principle comes with experience — just like riding a bicycle. You'll make some mistakes along the way as you learn how to do it well, but don't be afraid.

Try it! You'll love it, and you'll take pride in what you accomplish. And then you won't be able to imagine the world without it. ■

M.F., M.R.

BUSINESS

Data Reporting, Diagnostics, Sensors and NLCs Added to ANSI C137.4-2021 Standard for Digital Lighting Control

Harmonization of international standards related to DALI lighting control continues with the publication of the updated ANSI C137.4-2021 standard in North America. ANSI C137.4-2021 builds on the international standard IEC 62386 (which underpins the DALI communication protocol) and has additional characteristics and features that align very closely with the D4i family of specifications from the DALI Alliance, a global lighting-industry organization.

“We welcome the further alignment of ANSI C137.4-2021 and D4i, which is expected to lead to more availability of D4i certified and interoperable drivers, sensors, controllers and smart luminaires,” said Paul Drosihn, DALI Alliance General Manager.

D4i and ANSI C137.4-2021 specify the digital communication interface between luminaires and devices including sensors and network lighting controllers (NLCs). As well as including power-supply requirements, the standards define data models based on memory banks that enable the exchange of data. Implementation of these standards enables smart, connected luminaires, as well as interoperability between LED drivers and luminaire-mounted control devices.

ANSI Standard
ANSI C137.4-2021, an American National Standard for Lighting Systems, is entitled “Interoperability of LED drivers and other connected devices via the Digital Addressable Lighting Interface”. The DALI Alliance is a member of the ANSI Accredited Standards Committee (ASC) C137 on Lighting Systems, which developed and updated the standard. Approved in November 2021, the new version has now been published by the National Electrical Manufacturers Association (NEMA).

The earlier ANSI C137.4-2019 specified the power characteristics of the digital interface, including both an integrated bus power supply capability and an optional auxiliary (AUX) power supply. The standard also included luminaire-specific data stored in memory bank 1, per the DiiA Specification DALI Part 251.

The expanded ANSI C137.4-2021 now includes energy reporting data (referencing DALI Part 252) and diagnostics and maintenance data (from DALI Part 253). Also included is DALI Part 351, which specifies the characteristics of control devices that are used in or mounted on a luminaire. Further technical details can be found below.

D4i Certification
With a focus on interoperability, the DALI Alliance offers D4i certification of LED drivers and control devices. Certification involves rigorous testing, followed by independent verification of the test results, and certified D4i products are listed in the DALI Alliance’s online Product Database. There is no verification or certification scheme for ANSI C137.4-2021, but products that are compliant with ANSI C137.4-2021 may be eligible to apply for D4i certification.

D4i-certified control devices meet the requirements of ANSI C137.4-2021. The same applies for LED drivers, with the extra condition that if the driver has an integrated AUX power supply then it must be rated Class-2 or equivalent in compliance with the safety requirements of NFPA-70. ANSI C137.4-2021 has some further options – a 2W AUX power supply is possible, and also a Logic Signal Input (LSI) – which if implemented have associated requirements on top of D4i certification.

Technical Details
The digital interface specified by D4i and ANSI C137.4 includes a bus power supply (BPS) integrated in the LED driver, as described in DALI Part 250. There is also provision for an optional auxiliary power supply (AUX) to provide an additional source of power for connected devices. A 3W, 24V AUX supply is specified in DALI Part 150, while ANSI C137.4-2021 additionally allows a 2W, 24V AUX supply which is only suitable for a single connected device.

DALI Part 251 defines luminaire-specific data stored in memory bank 1. Luminaire OEMs can program a range of data into the driver—such as luminaire identification codes, nominal light output and even housing colour—that can be used for asset management in the field.

DALI Parts 252 and 253 specify further information that is accessible through the LED driver’s memory banks, and set requirements that support data exchange. DALI Part 252 enables real-time reporting of energy usage data, while DALI Part 253 specifies data for diagnostics and maintenance, which can be used for fault finding and preventative maintenance scheduling.

DALI Part 351 contains requirements for luminaire-mounted control devices, and includes specific requirements for power consumption, as well as a mechanism to decide which control device takes priority when more than one is present.

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

The Illuminating Engineering Society and the International Ultraviolet Association Release a New American National Standard for Measuring Ultraviolet LEDs

The Illuminating Engineering Society (IES, est. 1906), in partnership with the International Ultraviolet Association (IUVA, est. 1999), has published its first in a series of American National Standards for the measurement of ultraviolet product emissions. Since its discovery in 1877, germicidal ultraviolet disinfection has been deployed globally to reduce the rate of transmission of tuberculosis and other airborne pathogens in indoor spaces, including SARS-CoV-2, the virus that causes COVID-19. The standard published today, ANSI/IES/IUVA LM-92-22 Approved Method: Optical and Electrical Measurement of Ultraviolet LEDs, details a repeatable method for laboratory measurement of optical and electrical performance characteristics of UV light emitting diodes (LEDs), the discrete components built into UV LED products. This American National Standard is available for purchase at store.ies.org and is immediately available to IES Lighting Library subscribers.

“We are delighted to have partnered with the IUVA to develop these first-ever standardized methods of measurement for ultraviolet emissions,” said Brian Liebel, IES director of standards and research. “These standards will advance the science and application of germicidal ultraviolet disinfection, in support of our Society’s mission to translate lighting knowledge into actions that benefit the public. The dedication by our Testing Procedures Committee and the IUVA to completing this new industry standard has been outstanding.”

”Ultraviolet measurement standards provide the foundation for scientific trust of this key disinfection technology, and with this formal approval of ANSI/IES/IUVA LM-92-22, we are excited at what the future holds for optical and electrical measurement of UV LEDs as well as future standards to support our industry,” says Jennifer Osgood, president of IUVA; VP, CDM Smith. ”These standards would not be

possible without our continued partnership with IES. Our collaboration and cooperation are paramount to the success of our industry and reinforces our shared commitment to improving public health through ultraviolet disinfection."

ABOUT THE ILLUMINATING ENGINEERING SOCIETY (IES)
Established in 1906, the Illuminating Engineering Society is the recognized technical and educational authority on illumination. Our mission is to improve the lighted environment by bringing together those with lighting knowledge and by translating that knowledge into actions that benefit the public. We provide a variety of professional development, publications, networking and educational opportunities to our membership of engineers, architects, designers, educators, students, contractors, distributors, utility personnel, manufacturers and scientists in nearly 60 countries. Through our American National Standards Institute (ANSI) accredited process, we publish and maintain the Lighting Library®, with over 100 standards written by subject matter experts in our technical committees. In all our efforts, we strive to improve life through quality of light. To learn more about us, visit www.ies.org.

ABOUT THE INTERNATIONAL ULTRAVIOLET ASSOCIATION
The International Ultraviolet Association (IUVA) was founded in 1999. IUVA is devoted to the advancement of ultraviolet technology for public health and the environment–with activities including advocacy, education, collaborations, research and public policy engagement. IUVA is devoted to promoting science, technology, and engineering worldwide, for the global advancement of ultraviolet technology. ■

GLA Releases Guidelines for Quantification of Airborne Pathogen Inactivation by Ultraviolet Germicidal Irradiation

The Global Lighting Association has issued a Position Statement containing guidelines for measuring the inactivation of airborne pathogens by ultraviolet germicidal irradiation (UVGI) technologies. The guidelines are particularly relevant in the battle against COVID-19.

UVGI air disinfection technology is an established method for reducing infection risks caused by a wide range of contagious airborne diseases such as measles, influenza and tuberculosis. It follows that UVGI is a key tool in reducing the level of indoor air contamination posed by the SARS-CoV-2 virus. Pathogen inactivation theory and mathematical modelling are well established and described in existing UVGI literature.

The Position Statement outlines a methodology for quantifying the microbial cleaning capabilities of a UVGI product in a test chamber. These results can then be used to determine the product's disinfection capabilities in real-life applications such as class rooms, offices, hospital wards, restaurants, etc.

The Global Lighting Association calls on an appropriate standards development organisation to further refine the methodology contained in the Position Statement.

Guidelines for Quantification of Airborne Pathogen Inactivation by UVGI Technologies may be downloaded from the Global Lighting Association's website.

About the Global Lighting Association
The Global Lighting Association is the voice of the lighting industry on a global basis. GLA shares information on political, scientific, business, social and environmental issues of relevance to the lighting industry and advocates its position to relevant stakeholders in the international sphere. ■

Transition to DesignLights Consortium's Solid-State Lighting V5.1

With the grace period for updating LED products to meet its latest solid-state lighting (SSL) technical requirements set to expire on June 30, the DesignLights Consortium issued a reminder that products not updated to its Version 5.1 SSL Technical Requirements will be delisted from the DLC SSL Qualified Products List (QPL) as of July 1, and may therefore become ineligible for energy efficiency incentives.

Manufacturers must submit applications to update their products to Version 5.1 of the SSL Technical Requirements by April 15 to avoid delisting of non-V5.1 compliant products from the QPL – a resource utilized by more than 200 energy efficiency incentive programs across the US and Canada. The DLC's V5.1 SSL Technical Requirements took effect July 1, 2021, with a one-year grace period to give manufacturers time to update products and maintain their QPL listing. For distributors, manufacturers' representatives, energy services companies and others, now is the time to evaluate inventory to ensure that the commercial lighting products they stock and purchase are aligned with this new policy and will remain eligible for rebates.

"The latest technical requirements are aimed at improving the lighting quality and controllability of QPL-listed fixtures," DLC Executive Director and CEO Christina Halfpenny said. "Many commercial lighting energy efficiency programs recognize the importance of features such as dimmability and integral controls and rely on SSL V5.1 compliance for incentive programs."

The new policy requires manufacturers to report performance data on attributes such as color and discomfort glare based on light distribution, enabling QPL users to better distinguish characteristics needed for various purposes and installations. V5.1 also requires disclosure of integrated controls and ensures that most QPL-listed products can be dimmed, a critical component for capturing savings beyond those possible with LEDs alone and for integrating lighting with other building systems. Since LED luminaires installed today may last for a decade or more, strengthening controllability requirements locks in potential energy and cost savings for years to come. Not doing so can leave these savings stranded.

Introducing rigorous, attainable criteria for quality of light characteristics supports the DLC's intention to keep pace with technological advances to create solutions for a better future through better lighting. The DLC provided a grace period for manufacturers to update their products to keep them on the SSL QPL. After June 30, however, the DLC will delist any products not updated to comply with V5.1.

More information on transition to the SSL Technical Requirements, including industry guidance, is available here: designlights.org/our-work/solid-state-lighting/transition-to-ssl-v5-requirements/.

About the DesignLights Consortium:
The DLC is a non-profit organization improving energy efficiency, lighting quality, and the human experience in the built environment. We collaborate with utilities, energy efficiency programs, manufacturers, lighting designers, building owners, and government entities to create rigorous criteria for lighting performance that keeps up with the pace of technology. Together, we're creating solutions for a better future with better lighting. ■

DOE Finalizes Two New Rules for General Service Lamps

The U.S. Department of Energy (DOE) today adopted two new rules for light bulbs, also known as general service lamps, that will conserve energy and help consumers save on their energy bills. The first rule establishes a revised definition of general service lamps while the second implements the minimum standard of 45 lumens per watt for light bulbs that meet the revised definition. These rules are part of 100 energy efficiency actions the Biden Administration is completing this year, which together will save families $100 every year.

Once these light bulb rules are in place, DOE expects consumers to save nearly $3 billion per year on their utility bills. In addition to delivering significant cost savings for households, schools, and businesses, these energy efficiency actions also advance President Biden's climate goals. Over the next 30 years, the rules are projected to cut carbon emissions by 222 million metric tons — an amount equivalent to the emissions generated by 28 million homes in one year. LED lightbulbs also last 25 to 50 times longer than incandescent bulbs.

Appliance and Equipment Standards Rulemakings and Notices
"By raising energy efficiency standards for lightbulbs, we're putting $3 billion back in the pockets of American consumers every year and substantially reducing domestic carbon emissions," said U.S. Secretary of Energy Jennifer M. Granholm. "The lighting industry is already embracing more energy efficient products, and this measure will accelerate progress to deliver the best products to American consumers and build a better and brighter future."

The new definition issued today will become effective 60 days after publication in the Federal Register, while the implementation of the Congressional efficacy standard will become effective 75 days after publication in the Federal Register. DOE has concurrently announced an enforcement policy that allows for a managed transition helping entities all along the distribution chain, including manufacturers, importers, private labelers, distributors, and retailers adjust their production and inventory. The enforcement policy contains two parts: a period of enforcement leniency and a period of progressive enforcement with an emphasis on transitioning production first.

Additionally, DOE will host a webinar on May 4, 2022 at 2 pm ET to discuss the enforcement policy and answer questions from regulated entities. For more details, read the full enforcement policy.

DOE's Building Technologies Office implements minimum energy conservation standards for more than 60 categories of appliances and equipment. ■

Signify Publishes its first-ever Climate Action Report

Signify (Euronext: LIGHT), the world leader in lighting, has published its first-ever Climate Action Report, illustrating the progress we're making in taking climate action across our entire value chain. In the first year of our ambitious five-year Brighter Lives, Better World 2025 sustainability program, we are on track to double the pace of the Paris Agreement 1.5°C scenario and have generated between 61% and 64% of Climate action revenues, contributing to our ambition to double our positive impact on society and the environment by the end of 2025.

- Remained carbon neutral in all our operations, a status we achieved in September 2020, using 100% renewable electricity
- On track to double the pace of the Paris Agreement 1.5°C scenario
- Generated between 61% and 64% Climate action revenues, on track with our 72% target for 2025

Climate change is one of the most important challenges we face. Pollution and overconsumption rapidly increase greenhouse emissions, warming the planet at an alarming rate. The 2021 IPCC report announced code red for humanity and laid out the disastrous effects of increased temperatures. Melting ice caps raise our sea levels, endangering coastal human settlements. Warmer ocean waters lead to acidification, diminishing animal life and vegetation. Higher temperatures cause more intense storms, floods, heavy snowfalls, and longer and more frequent droughts. And reduced freshwater availability limits our ability to grow food and crops.

"In 2021, the world was still warming faster than ever. There is a widespread sense of unrest that calls for action, not words, to minimize and avert the damage we, humans, have caused for the planet," said Eric Rondolat, CEO of Signify in the Climate Action Report. "For Signify, this means we need to amplify our efforts, not only in our operations, but across our entire value chain, and help our stakeholders play their role in minimizing the impacts of climate change." ■

Lumileds' 2021 Sustainability Report

Lumileds, a global leader in innovative lighting solutions, issued its 2021 Sustainability Report detailing the company's progress in supporting the transition to a low-carbon and sustainable economy. In the report, Lumileds highlights how its lighting solutions contribute to positive changes in energy usage, safety, and health and well-being. Lumileds follows a formalized sustainability agenda that identifies specific priorities and tracks progress.

Lumileds sustainability efforts are aligned with the United Nations Sustainable Development Goals (SDGs) and the company has identified four SDGs where the most significant contribution can be made: Good Health and Well-Being, Affordable and Clean Energy, Responsible Consumption and Production, and Climate Action.

Lumileds is committed to taking urgent action to combat climate change by developing energy-efficient LED lighting solutions and through its ongoing commitment to reduce greenhouse gas (GHG) emissions in its operations. In 2021, the company averted 8.60 million metric tons of use-phase Carbon Dioxide (CO_2) through its LED products.

Lumileds also reports a significant step forward towards fulfilling its strategic initiative to completely transition to electricity from renewable energy sources. Operations in Malaysia fully transitioned to 100% renewable electricity and operations in the United States transitioned to at least 40% renewable energy. This allows the company to reduce its Scope 1 and Scope 2 Carbon Footprint with more than 40%.

"Despite ongoing challenges associated with COVID-19 and other disruptive global events, the urgent need to accelerate decarbonization across the world has been top of mind," said Matt Roney, CEO. "As such, we are unwaveringly committed to reaching our sustainability goals, motivated by the 1.5 degree warming scenario boundary. Our scientists and engineers continue to increase product performance while achieving significant reductions in energy use, carbon emissions, and water consumption."

Lumileds also highlights how new microLED technology can further support carbon footprint reduction through energy efficient applications and enhance safety in automotive lighting applications. In the area of vehicle safety, the report covers the road-legal approval for LED retrofit light sources in Korea, Germany, Austria, and France, bringing the safety benefits of LED lighting to new cars and, importantly, to cars already on the road. Complete details on Lumileds sustainability efforts can be found on our website at https://lumileds.com/sustainability. ■

Blueglass to Aquire US Laser Diode Facility

Australian semiconductor developer BluGlass Limited (ASX: BLG) is pleased to announce that it has reached agreement to acquire a commercial Silicon Valley laser diode production facility lease and manufacturing equipment (the Fab) for US$2.5 million. The acquisition will fast-track BluGlass' growth strategy, significantly increasing its laser diode manufacturing capacity and bringing forward higher-value product development timelines.

To fund the acquisition and ongoing operation of the production facility, BluGlass has secured A$3.4 million via a Placement to new and existing institutional and sophisticated investors. The Company is also undertaking a non-renounceable 1:4 Entitlement Offer to raise up to a further A$7.5 million to enable shareholders to participate on the same terms as the Placement.

Commenting on the strategic acquisition, BluGlass' President Jim Haden said:

"We plan to take advantage of a unique opportunity, to acquire a full-suite commercial laser diode fab for a fraction of the circa US$40 million it would cost us to build today. The acquisition aligns and accelerates our longer-term growth plans, bringing core fabrication processes in-house to eliminate supply chain variability and improve the quality and consistency of our laser diodes. Importantly, it provides us with greater control over development roadmaps, enabling us to launch higher-value products sooner.

"In addition to more than quadrupling development, manufacturing turns and wafer capacity, our own fab enables us to halve production costs and has the potential to bring forward positive cashflows to 2024/2025. It triples our revenue generation capacity, and allows us to execute on our strategic vision of becoming the industry's easiest-to-use laser light by offering the most flexible and agile product development and manufacturing. As one of just four end-to-end gallium nitride laser diode manufacturers globally, we have a significant opportunity to build share within a fast-growing market expected to reach US$2.5 billion by 2025.

"The acquisition will fast track our transition from a cutting-edge R&D company to a commercial provider of industry-leading GaN laser diodes. Over the past year, we have attracted industry experts to our management and Board, advanced our product development of multiple laser products and are delivering against a clear commercialisation and growth strategy. A Silicon Valley-based fab increases our access to highly skilled semiconductor and GaN talent even further.

"We're encouraged by the strong ongoing support of our existing investors, and welcome new institutional funds to the register at a pivotal period for the Company. BluGlass is focused on the commercialisation of our first direct-to-market laser diodes. We remain confident about our future. We have the right team and strategy in place and are now in the process of securing the final piece of the puzzle, a manufacturing fab to further expand our product offering and scale our operations."

ams OSRAM Signs Agreement to Sell AMLS – The Dedicated Lighting Systems Unit

ams OSRAM announced the agreement to sell the independent and dedicated AMLS (Automotive Lighting Systems GmbH) business to Plastic Omnium (Euronext: POM) for a purchase price of EUR 65 million. The transaction represents a further step in the implementation of ams OSRAM's previously communicated strategy to focus on dedicated strategic core technology and divesting businesses that are not seen as core to the corporate strategy. ams OSRAM will continue to be a key supplier of automotive LED and optical components to Plastic Omnium. This transaction does not include other ams OSRAM technologies and products for automotive OEM and the automotive aftermarket.

ams OSRAM Automotive Lighting Systems GmbH was established on 1 October 2021 following the dissolution of the OSRAM Continental joint venture. Headquartered in Munich, AMLS combines lighting technology with electronics and software to develop smart and innovative full lighting systems for the automotive industry.

As an industry leader in automotive optical solutions, ams OSRAM will continue to provide the high-tech innovation in components for automotive, including automotive lighting, covering the entire light spectrum – from visible to invisible light – and sensing applications for the automotive industry. This includes key automotive technology to support optical applications such as driver and interior monitoring, dynamic and static exterior lighting, RGB interior lighting, LiDAR for autonomous driving and advanced driver-assistance systems (ADAS), head-up display, gesture sensing to name but a few areas of innovation.

Dr. Dirk Linzmeier, General Manager of AMLS, comments on the acquisition: "The combination of Plastic Omnium and AMLS makes perfect sense. Our portfolios are highly complementary, together we expect to expand our market access and we share a similar mission and mindset. We look forward to joining Plastic Omnium to establish a strong mobility lighting player built on AMLS' portfolio of innovative technologies."

"The acquisition of AMLS is a unique opportunity to take an important step into the growing innovative lighting systems segment. Thanks to its advanced product portfolio, strong expertise, balanced footprint, and the quality of its team, this acquisition will allow Plastic Omnium to accelerate its ambitious strategy to meet growing OEM customer demand for smart body car parts and opens up the potential to enter new market segments. We are excited about this latest addition to the Group," said Laurent Favre, CEO of Plastic Omnium.

The AMLS business generated EUR 148 million in revenues in 2021, has around 770 employees at nine locations worldwide, including 120 engineers working in five dedicated R&D facilities. With Plastic Omnium, AMLS will join a world-renowned and strongly growing Automotive Tier 1 supplier group with 30,000 employees serving a global customer base. Headquartered in France, the company posted an annual revenue of EUR eight billion for 2021.

The closing of the transaction is expected in the third quarter 2022 subject to customary closing conditions. ■

Bridgelux Appoints Dr. Yi-Qun Li as Chief Executive Officer

Prior to being appointed as the CEO of Bridgelux, Dr. Li was the co-founder of Intematix Corporation, and served as its CEO and Senior Vice President of Sales and Marketing. Dr. Li is highly regarded in the lighting industry—considered by many to be a pioneer in LED technology and its applications. Over the past 20 years he led multiple innovation initiatives in phosphor technology including silicates, lutetium garnets, coated narrow-band red and narrow-band green sulphates.

In recent years, two of Dr. Li's passion projects, F90 and Thrive, have had the most wide-ranging commercial impact on the industry. F90, which uses the novel KSF phosphors, has facilitated the confluence of high efficacy performance and high color rendering in the same package. Thrive, which uses multiple broad-blue chips in the same package, creates full-spectrum emission that matches the spectrum of natural light. Under his guidance, Bridgelux has expanded both programs into multiple SMD and COB products for both commercial and residential applications.

Dr. Li holds Doctorate and Master of Science degrees from Stevens Institute of Technology and a Bachelor of Science degree from

Northeastern University in China. To date, Dr. Li has published more than 50 scientific papers and holds over 120 issued US patents on a wide variety of technology including LED phosphor compositions, remote phosphor structures, and LED devices. Dr. Li has also served as Research Professor at Stevens Institute of Technology, Research Engineer at semiconductor companies EMCORE and ATMI, and held executive positions at start-up companies NZ Applied Technologies and Spinix Corporation.

"When you think about the enabling technologies that have allowed LEDs to dominate, nothing has had more impact on performance, cost and quality of LEDs as the improvements in phosphor technology," says Don Peifer, founder of Smash the Bulb, who along with Bridgelux was recently recognized by the DOE as a concept phase winner for the prestigious L-Prize. "Dr. Li and Bridgelux are critical contributors to the state of the art we all enjoy as both an industry and as consumers."

About Bridgelux
Bridgelux is a leading developer and manufacturer of lighting technologies and solutions that invites companies, industries, and people to experience the power, possibility, and financial potential of LED lighting. Born of world-class engineering and informed by human intuition, the company's products and solutions make it possible for its customers to provide high performance, human-centric influenced light for the commercial, industrial, and outdoor markets. For more information about the company, please visit bridgelux.com. Bridgelux, the Bridgelux stylized logo design, Vesta, and Vero are registered trademarks of Bridgelux, Inc. Bridging Light and Life, Thrive, and V Series are trademarks of Bridgelux, Inc. All other trademarks are the property of their respective owners. ■

TECHNOLOGIES

LUXEON 5050 HE LEDs with Higher CRI and Efficacy

Lumileds is responding to market demands for better outdoor and industrial light and very high efficacy by expanding its LUXEON 5050 HE LEDs with new 80 and 90 CRI parts while simultaneously increasing the efficacy of the parts that are available in both 6V and 24V configurations.

"When given the choice, OEMs and end-customers want higher quality light, inside or outside, and they want it to be as efficient as possible," said Mei Yi Product Line Manager at Lumileds. "While others chose not to offer complete portfolios, we believe that supporting the broad range of applications, regional preferences, and requirements for light is the correct approach. Thanks to our phosphor, chip and package expertise, we are able to provide the range, quality, and robustness to support the most demanding applications."

LUXEON 5050 HE delivers industry-leading lm/W performance in high sulphur environments. 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 2200K – 6500K CCT with CRI of 70, 80, and 2700K – 5700K in 90 CRI. It is characterized for both illumination and horticulture with lumen and efficacy ratings as well as PPF (□mol/s) and PPF/W (μmol/J). Complete specifications and information for LUXEON 5050 HE can be found at https://lumileds.com/LUXEON5050HE.

Production orders can be place now for short lead-time delivery through Lumileds' distribution network.

About Lumileds
Lumileds is a global leader in OEM and aftermarket automotive lighting and accessories, camera flash for mobile devices, MicroLED, and light sources for general

illumination, horticulture, and human-centric lighting. Our approximately 7,000 employees operate in over 30 countries and partner with our customers to deliver never before possible solutions for lighting, safety, and well-being. To learn more about our company and solution portfolios, please visit https://lumileds.com. ■

High TLCI Illumination for Accurate Color in Telework & Indoor Video Recording

Nichia, the world's largest LED manufacturer and inventor of the high-brightness blue and white LEDs, announces the addition of the first mid power LED capable of delivering the high-quality light necessary to meet the demands of telework and indoor video recording.

Over the past 50 years, Nichia has demonstrated its commitment to improving the overall performance and quality of light through its R&D and production for phosphors and LEDs. Since its invention of the high brightness blue LED and subsequent white LED, simply replacing traditional lighting technologies with more efficient LEDs has never been Nichia's goal. The industry deserves, and can have more. Over the past several years, Nichia has aggressively reaffirmed the importance of "quality of light". How an object can be seen differently in light, or the level of personal comfort or wellbeing that such lighting provides, can sometimes be difficult to demonstrate through hard performance metrics. However, Nichia has been delivering new products based on this concept to show the value and importance of "quality of light", such as Optisolis™ which reproduces natural light, and the H6 Series which delivers vivid and beautiful colors while maintaining high efficacy.

The European Broadcasting Union (EBU) Technical Committee has defined one indicator to express quality of light, the Television Lighting Consistency Index (TLCI). TLCI quantifies the color reproduction of illuminated objects when they are projected on a display through a camera. Video and images taken under high TLCI lighting have higher color reproducibility than those taken under ordinary LED lighting, allowing users to enjoy natural, vivid, and beautiful images on TVs, PCs, and smartphone screens. The higher color reproducibility also makes it possible to reduce the time and cost previously spent on color editing.

Traditionally, TLCI has been an index that is often required for TV recording and broadcasting applications such as lighting in stadiums and indoor arenas. Nichia has had a high-power LED lineup with great TLCI metrics, specifically targeting stadium lighting, including the NV4WB35AM, NV4WB35AR and NVSW519A series. However, with the continued adoption of remote work as well as other new online activities, there is an increasing demand for indoor lighting with high color reproducibility through a camera, such as virtual meetings, video recordings and more. To respond to this demand, Nichia has developed and launched a TLCI option with the NFSW757G-P5H6/R9050j85t90, which achieves high TLCI metrics for lighting in indoor video production.

By combining Nichia's unique phosphor technology and the TriGain® Technology of GE Current, a Daintree Company, this LED achieves high TLCI, high color rendering / TM-30 and high efficiency at the same time, something not possible with existing high color rendering LEDs. This LED enables the design of luminaires appropriate for telework, online meetings, indoor video recordings and photography with smartphones. Nichia believes that this will greatly contribute to improving people's quality of work and life.

Nichia continuously explores how light brings value and enhances people's lives and will endlessly pursue the ideal light source. ■

NICHIA's Hortisolis™ LEDs Provide an Optimized Spectrum for Plant Growth

Nichia, the world's largest LED manufacturer and inventor of high-brightness blue and white LEDs, announces the launch of the Hortisolis™ Series of white LEDs. By incorporating only the light necessary for plant growth in one package through the delicate combination of phosphors, Hortisolis™ makes it possible to maximize the production efficiency per area of the vertical farm while providing a good working environment within the closed environments.

There has been a steady increase globally in the number of artificial farms that produce vegetables and fruits stably and systematically throughout the year without being affected by abnormal weather or natural disasters. There are two types of artificial farms: a closed one which solely uses artificial light without any natural sunlight, such as a vertical farm within a building. The other type is a solar-based green house that uses artificial light as a supplement to natural sunlight. In any case, while sunlight is free of charge, artificial light generates costs in equipment and energy. Therefore it is important to identify the necessary wavelengths for plant growth, and concentrate on those specific wavelengths to provide the light that can efficiently grow plants with as few lighting fixtures and energy as possible.

In Shanghai, China Nichia established its own vertical farm to further prove out research and implementation for each application, including plant growth. Utilizing its competencies in LEDs and phosphors, Nichia performed many experiments in the vertical farm, studying the three types of photoreceptors within the plant and their shade avoidance response behaviors. When plants determine they are in the shade of another plant, they respond by extending their stems to obtain a better light environment. Subsequently, Nichia finally succeeded in developing and commercializing the Hortisolis™ Series of white LEDs which simultaneously achieves the maximum production efficiency per area and also the comfort and efficiency of the workers.

Nichia believe the Hortisolis™ Series of white LEDs could contribute to solve the issues of food shortage generated by abnormal weather or natural disasters globally.

Nichia continuously explores how light brings value and enhances people's life, and will endlessly pursue the ideal light source. ■

LUXEON SunPlus Horticulture Portfolio Grows with the Addition of High Power Deep-Red: LUXEON SunPlus HPE

Lumileds announced its new LUXEON SunPlus HPE, a high power, deep-red (660nm) LED designed specifically for the horticulture lighting industry. LUXEON SunPlus HPE achieves the highest PPF and PPE from its industry standard 3.5mm square ceramic package. The new deep-red LED is part of the SunPlus horticulture portfolio that covers a broad range of wavelengths and colors, including white, purple, and lime, in a variety of mid-power, high-power, and CoB packages which offers flexibility to growers to create a specific Lighting mix required for various types of crops to give growers the edge.

"Much of the horticulture market is adopting solutions that use a mix of white and deep-red LEDs," said LP Liew, Senior Product Marketing Manager at Lumileds. "The new LUXEON SunPlus delivers top notch performance. And it's available with extremely short lead-times. At the end of the day, it's the highest performing LED and its shipping."

LUXEON SunPlus HPE has the robustness to stand up to harsh horticulture environments and deliver the longevity expected of all LUXEON LEDs. It pairs exceptionally well with our High efficacy LUXEON SunPlus 3030 and 5050 LEDs, the two most commonly deployed white LEDs. This white and deep-red horticulture combination can significantly drive down the system cost and reduce operating costs due to the solution's superior efficacy.

The LUXEON SunPlus HPE with its industry standard package has various off-the-shelf optical solutions available to enable designers to select the right viewing angles to achieve the appropriate intensity of Light for the crops. LUXEON SunPlus is a single portfolio engineered to address the full breadth of horticulture lighting applications.

For more information about LUXEON SunPlus HPE and to access the datasheet, click here. To view the entire LUXEON SunPlus horticulture portfolio visit https://lumileds.com/products/horticulture-leds. ■

Circular Economy LED Driver

Larger operating windows and slim housings even at high wattages are the stand-out features of Tridonic's new GEN4 LED driver platform. The first two versions are now being launched. These drivers are also the first LED drivers to have the EMC (Externally Managed Components) sustainability declaration.

EXC4 flexC lp LED drivers in dimming and non-dimming versions are suitable, in particular, for use in LED area luminaires. Thanks to large operating windows a single driver can cover a large number of possible applications. As a result, luminaire manufacturers can reduce the number of products they hold in stock without suffering any gaps in output ranges for their luminaires, even for high wattage types.

The narrow, low-profile housing gives designers enormous freedom to create slim luminaires. All the driver types of the GEN4 platform have a height of 16 millimetres to support the ongoing trend for miniaturized luminaires.

On the dimmable version the one4all interface provides a number of different dimming options. The software enables energy, lighting and diagnostic data to be read, thanks to the Tridonic lumDATA features.

All the GEN4 drivers feature an NFC interface so they can be quickly programmed in production, and easily adapted wirelessly even if they have already been installed. If a change is required the devices can be reprogrammed at any time via this wireless interface. If a device is replaced the data can be quickly and easily transferred to the new device. Or the luminaire properties can be reprogrammed on site without having to replace the luminaire. With NFC multi-programming, up to ten devices can be programmed in a single step.

For a sustainable circular economy
The new drivers support the transition to a circular economy based on the Cradle to Cradle principle. EXC4 flexC lp drivers have an EMC (Externally Managed Components) declaration so luminaire manufacturers can use this component in their products without the need for any further action for their Cradle to Cradle certification project. EMC means that the component does not have any harmful effects on humans or nature during normal use. In view of the materials selected for these drivers, Tridonic as the first supplier can take responsibility for the Cradle to Cradle suitability of the drivers.

EMC is a critical step towards Cradle to Cradle certification and part of the "Sustainable Tridonic" programme. Through this initiative, the company is developing products and solutions that comply with the concept of the circular economy. Another factor is that the new-generation LED drivers offer a greater number of possible applications while reducing resources, thanks for example to the larger operating windows. Tridonic wants to support customers in developing sustainable products.

Cradle to Cradle certification is the global standard for products that are manufactured for recyclability and includes requirements based on the criteria for sustainable product life cycles, namely prevention of waste, material savings, responsible use of resources and reduced consumption of rare materials. ■

Bright Future for micro-Pixelated Light, Prof. Martin DAWSON, University of Strathclyde, Glasgow, UK

Professor Martin DAWSON
Prof. DAWSON is one of the world's leading researchers in the field of micro-LEDs. In 2021, Prof. DAWSON was awarded the Optica/OSA's Nick Holonyak Jr Award and ISA's Global Solid State Lighting Award of Outstanding Achievement (the latter shared with Professor Hongxing Jiang of Texas Tech University).

Professor Martin DAWSON of the University of Strathclyde, in Glasgow UK, is an internationally acknowledged pioneer of the field of micro-LEDs, a technology of great interest worldwide for new forms of versatile and high-performance electronic visual displays. He has pursued a 20-year-plus vision of this technology involving extensive foundational and landmark device and systems' demonstrations, in particular based on capabilities offered by in-house fabrication of micro-LEDs and their integration with custom-designed CMOS. Prof. DAWSON's contributions to micro-LEDs have been recognized by a number of major international awards including, in 2021, both Optica/OSA's Nick Holonyak Jr Award and ISA's Global Solid State Lighting Award of Outstanding Achievement (the latter shared with Professor Hongxing Jiang of Texas Tech University).

LED professional: **Thank you for agreeing to this interview Professor Dawson. Perhaps we could start off with some personal and professional background.**

Prof. Martin DAWSON: I have been fortunate to have had a career that has exposed me to a wide range of (mainly solid-state and semiconductor based) photonics technologies and the applications of those technologies. This has produced a breadth of perspective, from materials through devices to systems demonstrators, which is very helpful scientifically and of particular value in identifying technological connections across discipline boundaries. A key theme throughout has been doing fundamental research work with potential applications in mind from the outset, what some would call 'use-inspired basic research'.

I started out in the early 1980s as a PhD student at Imperial College in London, working on ultrafast lasers, nonlinear optics and streak cameras. This also introduced me to optical spectroscopy of semiconductors and semiconductor lasers based on early-stage III-V epitaxy at Philips Research Labs, Redhill, UK. My research supervisors from that time (Wilson Sibbett and Roy Taylor) have provided much-valued mentorship and encouragement throughout my subsequent career.

I then spent five years as a post-doctoral researcher (and subsequently visiting assistant professor) in the USA - first in Texas and then in Iowa - continuing to develop novel ultrafast laser technology which was commercialized but also broadening and deepening my knowledge of nonlinear optics and carrier dynamics in semiconductors, in particular using III-V structures provided by Hughes Research Labs., Malibu, California.

I returned to the UK in 1991 to join the then newly-formed Sharp Laboratories of Europe Ltd. in Oxford. This was exciting as we were starting this industrial research laboratory entirely from scratch. The challenge was to establish a novel R&D program that fitted the company's commercialization timescales and strategy and we managed to do this by focussing on red-emitting AlInGaP/GaAs semiconductors for LEDs and lasers, important at that time for emerging applications in e.g. digital versatile disk (DVD) optical data storage. Initially we worked with material grown to our specifications by EPI (subsequently renamed IQE) Ltd., Cardiff, UK, later supplemented by in-house-grown gas source MBE wafers. We also initiated collaborative work with Nottingham University (Tom Foxon and John Orton, both ex-Philips) on gallium nitride semiconductors. This was my first exposure to gallium nitride and we had access not only to Nottingham-grown material but also to early gallium nitride LED devices from Nichia; work commenced around 1993 and joint papers on gallium nitride with Nottingham appeared from around 1995, when this was still a very new field.

In 1996, I moved to the University of Strathclyde to join its newly established Institute of Photonics which focusses on applications-oriented R&D of potential relevance to industry. A return to academia in this special environment was attractive to me and I was the Institute's first technical employee. I have been there ever since, being promoted to Professor in 2001, Distinguished Professor in 2019 (when the designation was first created at the University) and holding the role of Director of Research, responsible for introducing, overseeing and supporting most of the research activity. Again we had an almost blank sheet to start from, but in what is in hindsight an amazingly short period of time and drawing on the background above, we had found initial opportunities in ultrafast lasers utilising semiconductor saturable absorber mirrors (SESAMs); gallium nitride epitaxy and device research (including micro-LEDs); GaAs-based 'dilute nitrides'; optically pumped semiconductor lasers; and (single-crystal) diamond photonics; and we also managed to establish a new cleanroom and microfabrication capability to support this research. The Institute has since grown to around 70 staff and PhD/EngD students and continues to thrive, broadening its interests from the baseline themes above. I'm sure we'll be exploring some of these topics in more detail in your further questions.

Then, in 2012, we had the opportunity to establish the first Fraunhofer research centre in the UK, the Fraunhofer Centre for Applied Photonics (Fh-CAP), operated as a legally independent affiliate of the Fraunhofer Gesellschaft in Germany. I hold the Headship (Scientific Directorship) of Fh-CAP in parallel to my contin-

Figure 1: Acceptance speech of laureate Professor Martin David DAWSON at the Global Solid-State Lighting 2021 Award ceremony.

uing University position in the Institute of Photonics and it is a key part of the joint role to stimulate and manage the R&D interactions between these two organisations. Again, we were challenged to start this Fraunhofer R&D centre from scratch, although of course with important support and advice from our colleagues in Germany. Fh-CAP took an initial technical positioning in scientific laser systems for metrology and instrumentation applications, linking to an area of historical core academic and industrial strength in the Central Belt of Scotland (Glasgow-Edinburgh corridor). Aligned to this, Fh-CAP was, and is, especially well placed to pursue an agenda in quantum technology - we realized that very early on. It is now prominent in the UK's National Quantum Technology Program across all main themes of quantum imaging, sensing, timing, communications and (increasingly) computation. This Centre currently sits at around 65 staff and students, and to date has had funded R&D collaborations in over 150 programs with over 100 companies.

LED professional: Could you explain what micro-LEDs are and how they differ from normal LEDs?

Prof. Martin DAWSON: The name micro-LEDs has really come to symbolize pixelated LED technology where the pixel size is in the range 1 to several 10's of microns in edge dimension or diameter. We tend (in our Institute) to use it a little bit more broadly than that for pixel sizes less than about 100 microns. The idea is that typically these structures are fabricated from conventional gallium nitride LED epitaxial wafers although they can be subject to specialized growth to try to optimize their characteristics. But because of their micron size they have a number of performance advantages and distinctive physical properties, and I think this is something that's not always well appreciated. People can think that it's quite a simple thing just to take a 300 micron diameter or a 1 mm square conventional chip sized LED and just shrink it down, and everything stays the same - but it doesn't. There are particular characteristics of how you can extract light from and image the output of those small pixels, how you can control them electronically, and how you can modulate them - and there's a lot of physics that is different, such as current density dependence, junction temperature behavior, modulation bandwidth, carrier lifetime effects and also field screening effects inside the devices.

With micro-LEDs you apply currents through a small device and you get very high current densities. You can drive milliamps through a single pixel and end up with current densities DC of kiloamps per square cm. This is one of the remarkable features of gallium nitride, that you can sustain these very high current densities in a robust device. It can affect the differential carrier lifetime and so affect the modulation response of the devices and it can allow enhanced field screening. There are also distinctive relationships to that high carrier density to things like how the efficiency droop characteristic of the devices looks. I should also say, associated with the small pixel size and high current density, that you're extracting the light from a small area so the optical power density that is emitted from the devices can be very high as well – watts per cm^2. That's also an enabler of the applications that you can have for micro-LED technology. Of course when you have such a small device you've got a lot of surface area to the active area and this has really brought to the fore the issue of surface recombination and effects on the internal and external quantum efficiency of these devices. So when you push down very small you know there is an extra challenge in how you maintain the efficiency of the devices. Hence there are good things and bad things in the physics, but the key point at the end of the day is that you have a device technology that can be produced in very high density 1D and 2D arrays and either directly viewed or imaged. That is really a key enabler, together with the brightness, the spectral selectivity and the fast response of micro-LEDs. All this really opens up the range of applications for this technology.

We've taken the view from the beginning that micro-LEDs would only become a mass market technology if it was implemented in conventional epitaxial structures. That's our view; others may see it differently. The work we've done is therefore almost exclusively on c-plane sapphire in the case of GaN on sapphire using conventional epitaxial LED structures or similar conventional type structures on silicon. Of course it's important to investigate characteristics such as the number of quantum wells in a device for a particular type of application. When you operate under these high current density conditions and you are trying to optimize for datacom or something like that there is a need to do systematic investigations on conventional chip substrate growth. It is also possible to fabricate micro-LEDs utilizing what might be termed specialized substrates to give e.g. semi- or non-polar devices. This can mitigate the effects of reduced electron and hole wavefunction overlap due to internal electric fields in more conventional structures which can affect the recombination, efficiency, carrier lifetime and so on. In principle, you can get around those types of limitations with non-standard growth substrates and that's a very fascinating area of investigation. Some groups are looking at these sorts of things, like at the University of New Mexico or the University of California Santa Barbara. A key question is if there is enough demand in the market to make an affordable and scalable commercial micro-LED technology out of growth on these non-standard substrates. Maybe micro-LED is the use case that will enable that.
The big commercial driver at the moment is obviously on the large area displays and wearable displays. A huge amount of effort has been put in by the commercial manufacturers to establish viable methods to assemble the required millions of micro-LED pixels onto electronic backplanes and interfaces. These include mass transfer, mechanical self-assembly and so on. There's a range of different things that commercial suppliers are really focusing on now and you can see the amazing success of the products that they are achieving. What we tend to look more towards is the digital light projection type of applications of micro-LEDs. There you may not need the area scaling that a display has. The most typical approach in that case, particularly in the case of the epi-structures on sapphire, is to flip-chip bond the micro-LED array onto a CMOS chip. Our new mega projector chip that's a couple of 10s of thousands of micro-LED pixels on about a 30 micron pixel size, each micro-LED with 50 micron pitch, is on a CMOS chip where each of those individual pixels has an individual CMOS driver - and that's done by bonding. The other approach that we've looked at is where the gallium nitride is grown on silicon and then there's a variety of ways in which you can detach that material from its growth substrate and transfer it over onto the electronics.

It's very straightforward to obtain green emission and blue emission for micro-LEDs using gallium nitride, but it's much more difficult to get efficient red. There

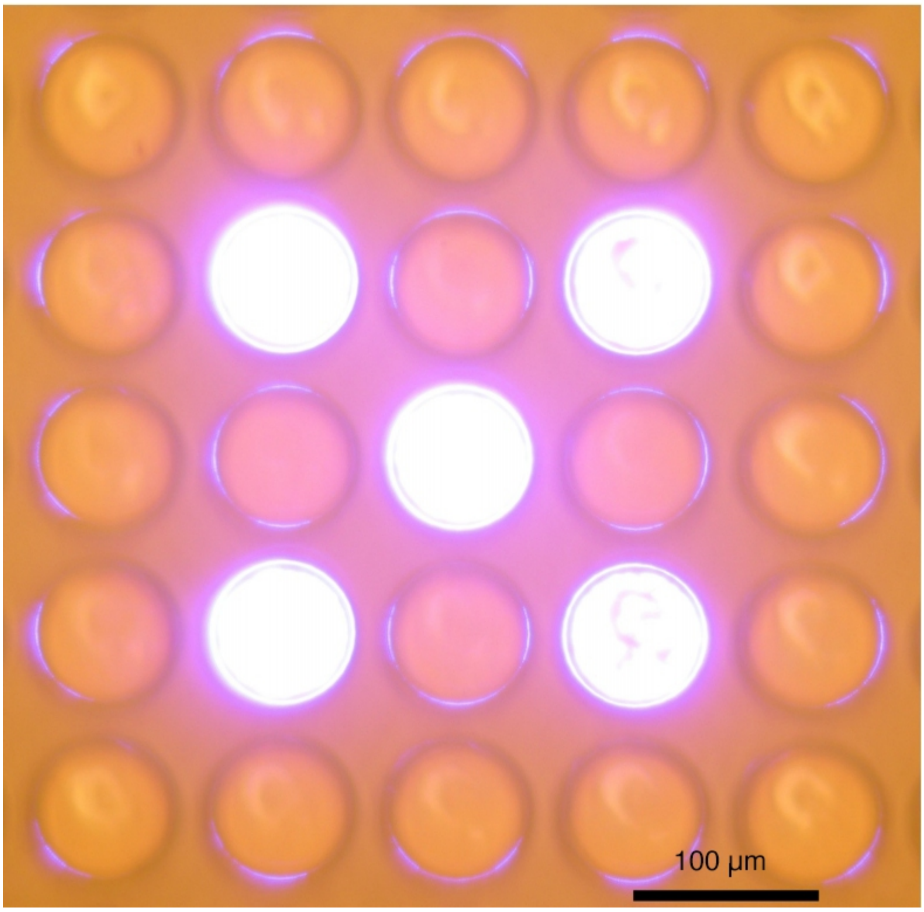

Figure 2: Plan view micrograph image showing a pattern displayed by a violet-emitting micro-LED array that is bump-bonded to a CMOS electronic control driver array.

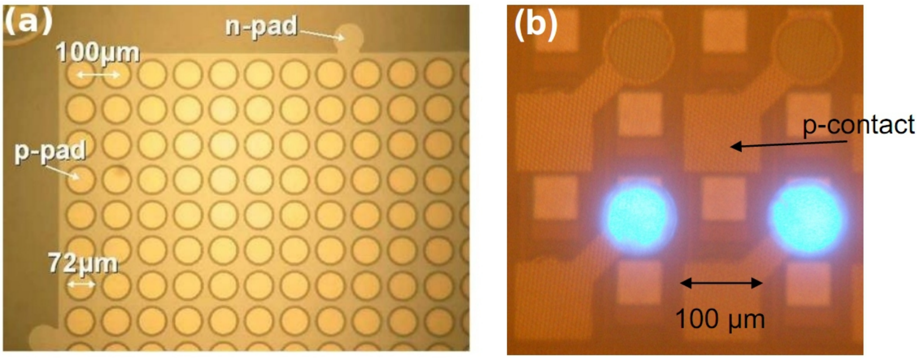

Figure 3: Plan view micrograph image showing section of a 16×16 individually-addressable micro-LED array (left). Micro-LED pixels that have been flip-chip bonded to a CMOS electronic control driver array (right).

are various ways in which you can try to do that in nitride material, for example having nanowire substructure within your micro-LED pixel, or you can incorporate rare earth materials into the nitride matrix. Alternatively you can down convert the blue or green emission using a photo-pumping technique with some sort of color converting overlayer that might, for example, be quantum dots or organic semiconductors. These are promising approaches that link to other types of display technology and they address challenges of using conventional rare earth type phosphors with micro-LEDs, such as the incompatibility of their grain size with the micro-sized pixels or being too slow in response time to match the fast response of the micro-LED being color converted. Overall, the commercial route that seems in favour for the emerging micro-LED display market at the moment is to use the alternative AlInGaP on GaAs material system for the red emission component. And then you need to have some sort of assembly technique that allows nitride based blue and green devices to be combined together with the red AlInGaP/GaAs emitters.

LED professional: Another point which seems to be different between micro-LEDs and standard LEDs is the timeline of the research and development phases. Both research starting points were quite similar - in the late 1990s and early 2000s - but the standard LEDs are quite mature now, whereby the micro-LEDs are still at a very early stage. Why is this?

Prof. Martin DAWSON: I think a lot depends on what the real focus area for industry is at any particular time. From the beginning of the nitride field, the technology has been principally industry driven. I would say the universities have provided (and continue to provide) a lot of the important background fundamental investigations but it is the companies that have driven the emergence of nitrides to commercial products. I guess it was really a matter of what products were the priorities on their roadmap. Early on, the key drivers were things like how do you make high-power, high-brightness conventional chip-sized LEDs, and how do you make white LEDs for lighting. Industry's attention was thus elsewhere than on micro-LEDs. They were not thinking about the possibility of nitride materials comprising a micro-display technology or a high-resolution display technology. So when groups like ours started things off in the micro-LED field, around 2000, we were very lucky because we had 15 years or so to explore the potential of the technology and build-up the use cases and generate the interest before our industrial

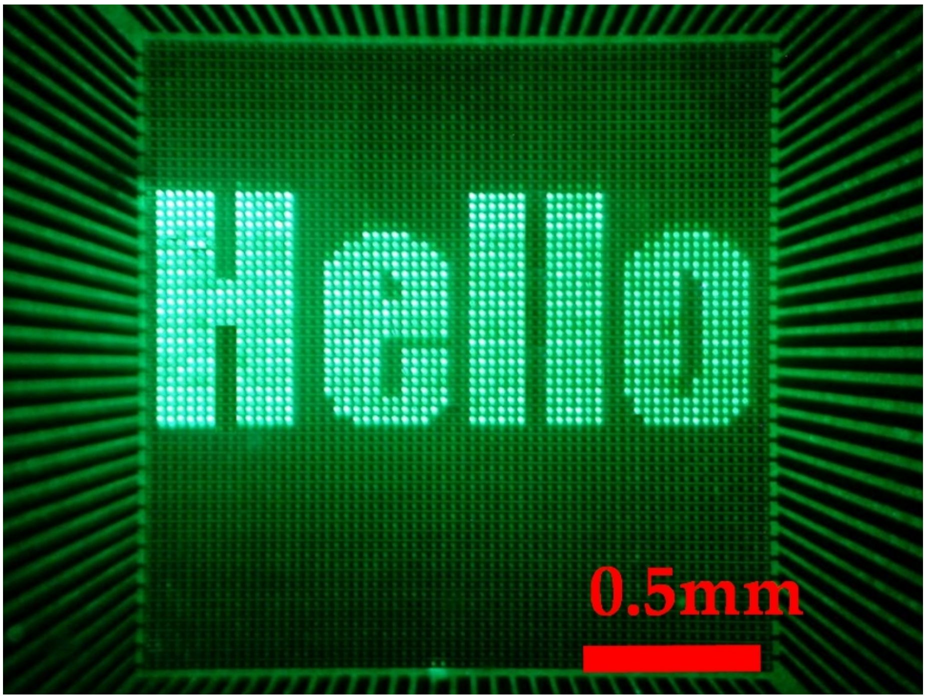

Figure 4: Plan view optical micrograph image of a green-emitting 128×128 matrix-addressable micro-LED array.

Figure 5: Plan view optical micrograph image of a blue-emitting 128×128 active-matrix micro-LED display, showing the University of Strathclyde crest. This chip is capable of up to 1 Million frames per second update rates.

colleagues properly saw the potential. But now industry is fully involved and really only it can solve the issues of assembling literally millions of these devices into displays with high uniformity and high-performance - that can't be done in academia. Overall, then, I would say that it wasn't that the potential market for micro-LEDs didn't exist early on, it was just that nobody had really thought of it.

LED professional: You have mentioned your introduction to gallium nitride in the early 1990s. Can you explain what approach you took in establishing gallium nitride research when you joined the Institute of Photonics at the University of Strathclyde?

Prof. Martin DAWSON: Work on the spectroscopy and microscopy of gallium nitride, from the perspective of materials science and fundamental light-matter interactions, was already underway in the Department of Physics when I joined Strathclyde in early 1996. My interest, aligned with the distinctive mission of the Institute of Photonics, was different: to do device research and development, via establishing capability for growing and processing gallium nitride. This was clearly dependent upon securing major capital equipment resources for epitaxy and micro-fabrication. We were successful in this, winning grant funding and building relationships with the companies Aixtron and STS (subsequently SPTS), respectively, to establish MOVPE growth and inductively-coupled plasma (ICP) dry etching capability, and subsequently receiving support from IQE to assist in recruiting a crystal grower (my long-time colleague Dr Ian Watson). All of this was in place by around 1999. Furthermore, engagement with Scotland's national enterprise agency (Scottish Enterprise) permitted a publicly-owned, industry-supporting off-campus fab and cleanroom facility to be specified and built, to house this university-owned equipment alongside other capability. This was named Compound Semiconductor Technologies (from which emerged Compound Semiconductor Technologies Global, now Sivers Photonics).

To my knowledge the above was the first new MOVPE system in the UK dedicated to gallium nitride growth and the UK's first ICP dry etching system so dedicated, and sitting these tools alongside each other was a crucial part of the vision for our research. The ICP etching, especially, has been a mainstay in our research over the past 25 years, permitting processing of a range of technologically interesting hard optical materials, including sapphire, silicon carbide and diamond as well as gallium nitride, materials whose characteristics we have explored individually, but also in combination: for example permitting substrate-based micro-optics (in sapphire or SiC) to be fabricated in registry with gallium nitride light-emitting micro-devices.

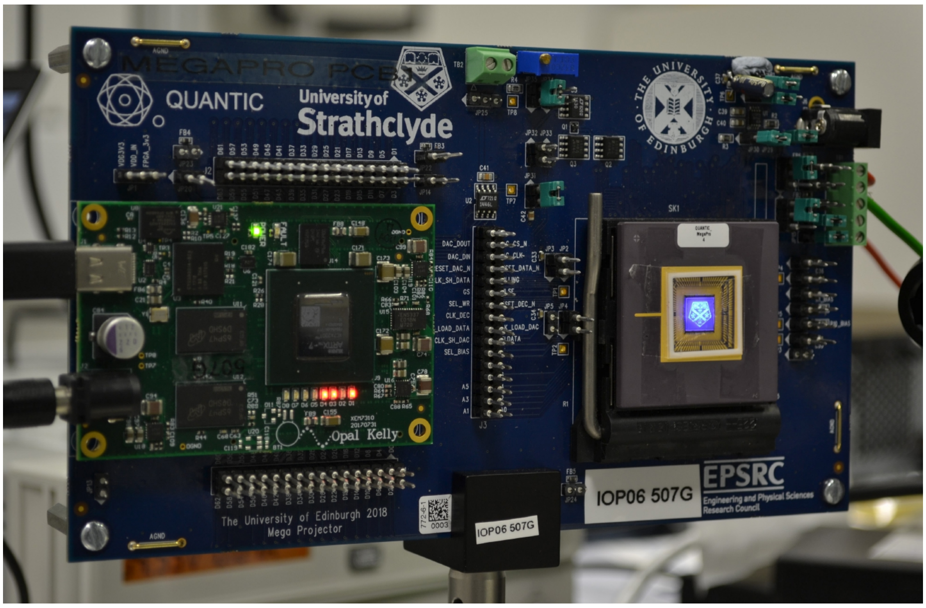

Figure 6: The Megaprojector micro-LED based digital light projection system developed under the EPSRC's 'Quantic' program.

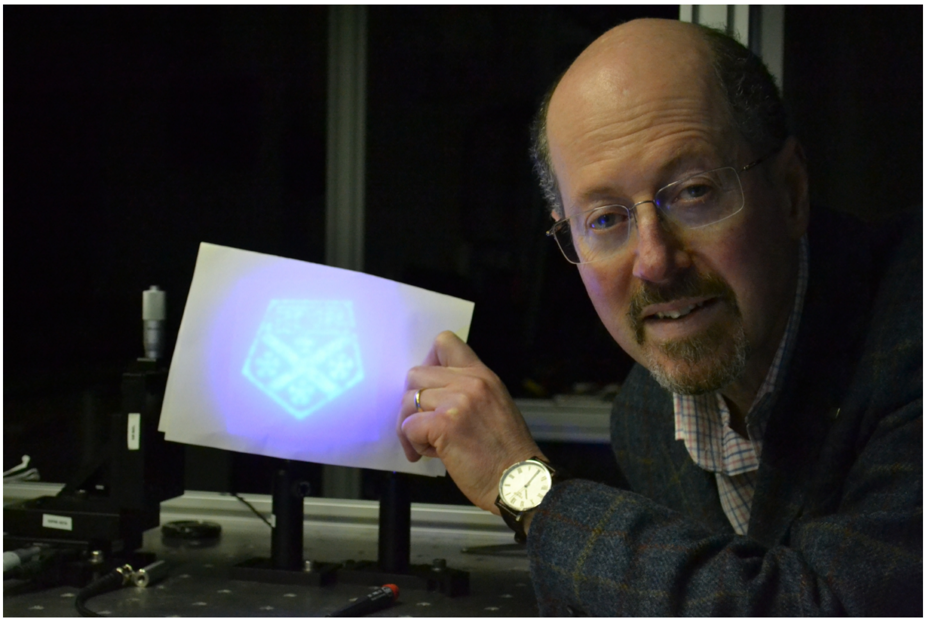

Figure 7: Projected light output of the University of Strathclyde logo, imaged at around two meters.

A couple of early interactions helped bring this new capability to maturity and attract some attention. First, colleagues in our Physics Department had arranged for future Nobel Laureate Shuji Nakamura (then still at Nichia) to be a visiting professor at Strathclyde. Dr Nakamura visited us several times in those early years and gave encouragement – he has been aware of our interest in micro-LEDs since the early 2000s. It was a particular pleasure that he was involved in the recent presentation ceremony of ISA's Global Solid State Lighting Award. Also, we established a collaboration on gallium nitride with the Samsung Advanced Institute of Technology (SAIT) at around the same time which initially included them sending us one of their research staff as a PhD student. This led to several excellent Korean researchers in succession being based in our group.

LED professional: When and how did micro-LEDs come into the picture in your laboratory?

Prof. Martin DAWSON: We were looking for a novel theme to differentiate our program and initially focussed on basic dry etching investigations of GaN, approaches to making GaN VCSELs and micro-optics, and on investigations of laser lift-off/laser micro-machining in GaN. We filed a patent which proposed that dielectric masks for epitaxial lateral overgrowth (ELOG) could be in the form of oxide-based distributed Bragg reflector mirror stacks, subsequently overgrown to provide a lower 'buried' Bragg mirror for GaN VCSELs whilst also improving the device active region above. We made and published some basic demonstrations of such overgrowth on dielectric mirrors and I was interested in recent years to see this approach successfully pursued to full GaN VCSEL implementation by Sony.

The studies above planted the seed of microscale GaN devices firmly in our minds. Hence when the very first papers on micro-LEDs appeared from the group of my good friends Professors Hongxing Jiang and Jingyu Lin (then at Kansas State University, now at Texas Tech) in 2000 this immediately made an impact. I felt that this was a technology we were well placed to contribute to, and so we started to design and process our own devices pretty much straightaway. We obtained funding for a 2-year initial program (2001 – 2003) on "GaN visible micro-LEDs for advanced displays" and began publishing our first results in 2001/02. By 2004, we had advanced the basic display demonstrations to arrays of 129 x 96 ≈10 µm-sized pixels and showed some basic image display capability at blue and green wavelengths (IEEE Electron. Dev. Lett. 2004). We also patented a sloped sidewall micro-pixel shaping approach which facilitated the conformal metallisation of these devices and helped in light extraction.

LED professional: How did your research into micro-LEDs develop and mature in the early years?

Prof. Martin DAWSON: A big step in our research was obtaining (2004 – 2008) a large grant on micro-LEDs under the UK EPSRC's (Engineering and Physical Sciences Research Council's) Basic Technology Program, which involved an extensive web of collaborations with other universities and research disciplines. Although much of the interest in micro-LEDs was - and is - focussed on direct-view display applications, we had a vision that this could be a new form of digital light projection technology suitable for a wide range of scientific and instrumentation applications, so we teamed up with other physicists, and with chemists, engineers, and materials scientists, to explore this. The core idea was of a pattern-programmable 'pico-projection technology' suitable for initiating, stimulating or controlling light-matter interactions at visible/UV wavelengths with materials as diverse as polymers and biological systems.

A lot came out of that program, including demonstrations of: micro-LEDs for direct-writing photolithography and associated manufacture of gene chips; micro-LED arrays in the near-UV; micro-LEDs for structured illumination wide-field optical sectioning microscopy; colloidal quantum dot color converters for down-conversion to enable multi-color operation of micro-LED arrays based on one epi-substrate. We introduced CMOS for active pixel driving and this included CMOS chips with single-photon avalanche photodiodes (SPADs), facilitating routes to highly-parallel chip-scale time-resolved fluorescence systems. This program began a long, continuing and very fruitful collaboration on CMOS-driven micro-LEDs (and SPADs) with our colleague at the University of Edinburgh, Professor Robert K. Henderson. In addition, the idea of optogenetics had just begun to emerge at that time, and this grant enabled, with colleagues at Imperial College, first demonstrations of micro-LED photo-stimulation of light-activated opsins in neurons. Many of these developments were collected together in a special cluster issue of J.Phys.D: Appl. Phys. (Vol, 41, May 2008).

Most of these demonstrations opened up really new areas and I also summarized these findings in an invited talk at the CLEO/QELS conference in 2008. Light emitting diode pioneer M. George Craford was in the audience and he seemed to react with interest when I mentioned driving the micro-LEDs by CMOS. A colleague who was there at the time and who saw that reaction said "you really got his attention". Perhaps momentarily - it's nice to think so!

LED professional: Please tell us something about industrial interest and engagement in your work.

Prof. Martin DAWSON: We'd always had in mind that this was a potentially commercializable technology. Indeed the initial funding I mentioned above, from our national enterprise agency in Scotland in 2001-2003, was given to us to develop the technology to the point of, and to explore options for, commercialization. We were therefore careful to retain core know-how and to file intellectual property when appropriate. For various reasons, in particular identifying and securing a suitable chief executive, it actually took until 2009 until we launched our spin-out company mLED Ltd. The University of Strathclyde was very helpful throughout these background preparations and in the launch of this company and its subsequent development. An excellent team was put together (including a microfabrication engineer/researcher from our group who had worked on micro-LEDs) who ran the business while I and my group continued in academia – they deserve a lot of credit, as do the Board of Directors. It is a matter of public record that the company was acquired in 2016 by a major multi-national business.

In parallel to the above, in the period around 2006-2016 we had regular contacts by and visits from (on their initiative) almost every multi-national consumer electronics business you can think of, and some you probably wouldn't think of. This still happens from time to time. All this was amazing to me, as at that stage we were circumspect in advertising this work outside of our research publications and conference talks. So it was clear that quite a few companies must already have been foresighting the technology at that stage or at least thought it promising enough to be worth keeping a watching brief on. They were clearly very well aware of our work.

Fraunhofer CAP has recently allowed a new avenue for exploring commercial exploitation of the technology. We are developing a number of strands of activity in Fh-CAP which use micro-LEDs, including in bioinstrumentation and optical communications. Very recently we have also launched a new company, Neuro-VLC, headed by former Institute of Photonics student Gabor Varkonyi, to develop wireless data communication neural interfaces based on LED emitters. We are really excited about this development and it will be fascinating to see how this business develops in the next few years.

LED professional: What's the status of mLED today?

Prof. Martin DAWSON: I can answer that simply, mLED no longer exists. In 2016 the company was acquired by a multinational corporation. It was operated as an independent business from 2009 to 2016 and then when it was acquired the staff moved with the assets, including IP. They were all taken up as part of the sale. This multinational involvement was a big signal to others that this technology was becoming a serious proposition and therefore you can see that everything has really ramped up commercially from around 2016. But in our university research group we are completely free to carry on our research as we have always done.

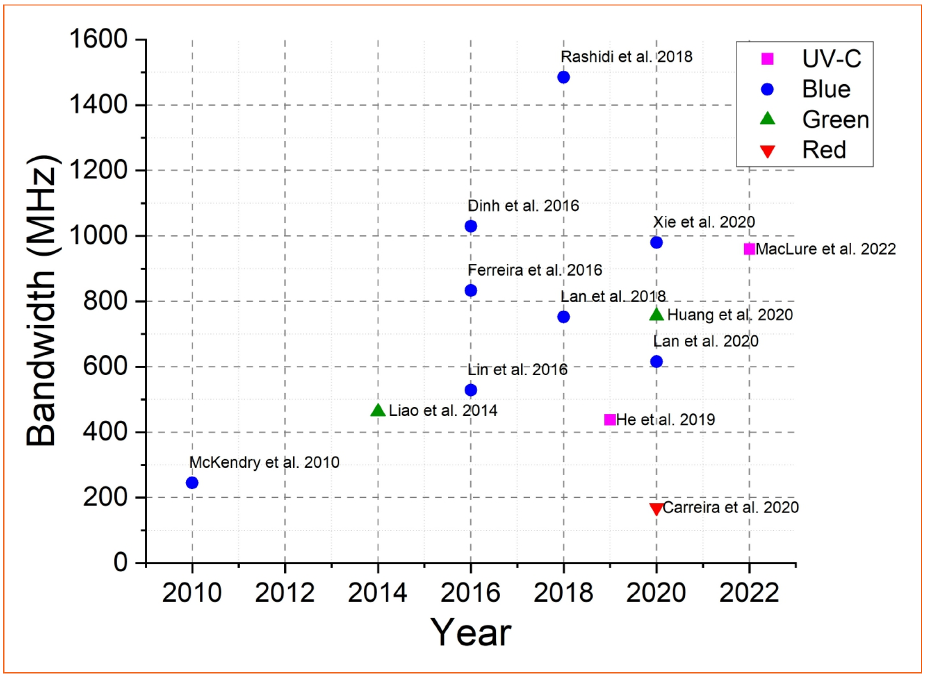

Figure 8: Graph showing the micro-LED optical bandwidths reported from selected publications versus year [1-13]. Carreira 2020 [1], McKendry 2010 [2], Liao 2014 [3], Lin 2016 [4], Ferreira 2016 [5], Dinh 2016 [6], Lan 2018 [7], He 2019 [8], Lan 2020 [9], Huang 2020 [10], Xie 2020 [11], Rashidi 2018 [12], Maclure [13].

LED professional: This acquisition was mainly driven by the display sector, we think. Do you see similar importance for the lighting sector, e.g. the automotive industry?

Prof. Martin DAWSON: It really depends what you're trying to do. We have been aware of potential automotive applications such as smart automotive headlamps, probably since around 2014. You can see the sense of it. If you have a pixelated light source and appropriate electronics control you can trim the beam or you can control the intensity and all kinds of things. That's smart illumination. I think broader applications in lighting may relate, for example, to LiFi and implementing sophisticated types of optical wireless communications or lighting based imaging and sensing functions in an office or room environment. I gave a talk at a conference in China a few years ago where I stood in front of one of those massive conventional LED screens. When the screen went white, it was really overpoweringly bright to stand in front of. And that's when you realize that LED displays are a lighting technology.

The vision that Professor Harald Haas has pushed over recent years is the idea that lighting and wireless communications capability are merging. What's effectively a display technology in the form of micro-LEDs has a role to play linked with that. If you look at these big panels that Samsung or Sony are developing - high-resolution large-area displays based on micro-LEDs - you could easily switch them all to white and make it a smart lighting technology and/or modulate the output quickly for data projection.

The question is, why would you need that degree of smartness and pixellation? But of course the lighting source could be very sophisticated - it just depends on what environment you want it to be operated in. It could be projecting data out into the room or it could be facilitating the recording of images, for example. Some of the work that we've been doing in recent years is recording images on a camera using a technique known as photometric stereo imaging. Instead of having your two eyes to get the 3D view of an object, you have a single camera or receiver and illuminate the object from multiple directions. Then you look at the shadowing on the objects and you can reconstruct depth images from that. These photometric stereo imaging systems normally have four illumination directions. We've been thinking that basically, you can have each corner of a big area display looking out into the room and a camera on top of, or even embedded in, the display itself. It's like a TV sensing the environment. It can in principle tell you where the viewer is and adjust what it shows, depending on where the viewer is sitting or something like that. The idea of micro-LEDs as a lighting source depends on finding these use cases that really require that level of smartness. The core strength of micro-LEDs is that it's a very sophisticated high framerate pattern projection or display technology and you really need to find applications in lighting that need that.

LED professional: How far along is the micro-LED technology for commercial applications, in general?

Prof. Martin DAWSON: The best resources to help understand that are reports and presentations from well-informed market survey organizations such as Yole Developpement. These organizations have a very good view of how the market is emerging and growing. But I think we will only really know in about five years' time whether this is a real broad impact technology for the display market or whether instead it will find its place in particular niches within that market.

What I'm very conscious of is that we should never underestimate the alternative technologies. People keep thinking that liquid crystal displays have run out of steam and then there's some new twist in the story that takes them to the next level. Then there are the OLED displays

Publication & Year		Modulation scheme	Maximum data rate (Gb/s)	Transmission distance (m)	Comments
McKendry et al. 2010	[14]	OOK-NRZ	1	n/a	
McKendry et al. 2012	[15]	OOK-NRZ	0.512	n/a	CMOS-controlled micro-LED array
Wun et al. 2012	[16]	OOK-NRZ	1.07	50	Transmission over polymer optical fibre (POF)
Maaskant et al. 2013	[17]	OOK-NRZ	0.5	n/a	Transmission over POF
Zhang et al. 2013	[18]	OOK-NRZ	1.5	n/a	Multi-channel transmission using CMOS-controlled micro-LED array
Tsonev et al. 2014	[19]	OFDM	3	0.05	
Li et al. 2015	[20]	PAM	10	10	Transmission over POF
Ferreira et al. 2016	[21]	OFDM	5	0.5	
Dinh et al. 2016	[22]	OOK-NRZ	2.4	Back-to-back	Semi-polar micro-LED
Rashidi et al. 2017	[23]		0.524	Back-to-back	Non-polar micro-LED
Liu et al. 2017	[24]	OOK-NRZ	1.3 / 1	3 / 10	
Islim et al. 2017	[25]	OFDM	7.91	n/a	
Rajbhandari et al. 2017	[26]	PAM	7.48	0.5	Optical MIMO using CMOS-controlled micro-LED array
Bamiedakis et al. 2019	[27]	PAM	2.5	50×10^{-3}	Transmission over 2D waveguide arrays
He et al. 2019	[28]	OFDM	1	0.3	UVC-emission (262 nm)
MacLure et al. 2020	[29]	OFDM	10	0.5	Three wavelength Ultraviolet Wavelength Division Multiplexing

Table 1: Chronological list of selected publications on VLC using micro-LEDs.

that are very well placed and have their market position and there are the q-dot displays too - so you know there's lots of competition there. But micro-LED technology has its own particular advantageous characteristics and I think there's a combination of the big multinationals who have the real resources and the driving power to really make this a mass market technology. We can see what companies like Samsung and Sony have done already, which is just amazing, and there are a lot of highly creative smaller businesses that are exploring particular niches. So I am confident in the commercial potential of micro-LEDs.

LED professional: Another application for micro-LEDs is in visible light communication. Can you tell us a bit about work in the field of VLC?

Prof. Martin DAWSON: There's a number of different types of environments and link scenarios where you can think of either guided wave use of micro-LED modulated data signals or micro-LED free space type communications applications, the latter even including possible deployment in satellites in space. There is application in polymer optical fiber based datacom systems but also for other areas as well such as underwater optical communications and in room lighting/LiFi scenarios. The key characteristics of micro-LEDs for these applications are low power consumption, simple components, a very high data rate capability and ability to communicate over significant distances as well as having the right wavelength characteristics for low-loss transmission in the different types of media and ability to generate white light when needed. But then you get other benefits from the fact that this is a display technology as well. There are ways to utilize the two-dimensional high-density array format of micro-LEDs for other formats of communication where you can communicate data aggregated from multiple emitter elements at once to give spatial modulation or spatial multiplexing.

The fact that micro-LED technology is very readily interfaced to CMOS and other sophisticated electronic control, means that you can embody very complex and capable data algorithms directly onto the high-performance comms capability, and this is a big part of what we do in our research. You can just drive the nitride devices that implement these types of advanced data encoding techniques and you get amazing performance from quite a simple device. What seems to be in prospect here is the trend that we have a display that is actually a very sophisticated optical communications interface. At the same time that you are watching a movie where you just need 30 or 40 frames a second, the interface could be communicating at a million frames a second that a camera can see. The camera may be interpreting quite different information from the display for a different purpose at the same time that you're watching the movie.

LED professional: How and when did visible light communications and LiFi come into the micro-LED picture?

Prof. Martin DAWSON: We ran three large, multi-partner EPSRC-funded programs on micro-LEDs back-to-back in the years 2004 – 2017. At the beginning of the second of those, around 2008, our (then) Imperial College London colleague Professor Gareth Parry drew my attention to visible light communications (VLC) and encouraged us to investigate how micro-LEDs might fit with VLC. The funding we held allowed flexibility in program directions, so we pivoted to this clearly important and rapidly developing area, establishing links with colleagues external to the program whom we realized could help – in particular Harald Haas, then at the University of Edinburgh, and Tony Kelly at the University of Glasgow. We started to look at the modulation bandwidth capability of micro-LEDs of various wavelengths from UV to green and quickly realized this could be 100's MHz – much higher than broader-area devices. Our first paper on this came out in 2010. We were also able to determine that carrier density dependent carrier lifetime effects were an important factor in this enhanced performance.

The real step-up in our effort on micro-LEDs for VLC and LiFi came with the successor program, which we called Ultra-Parallel Visible Light Communications (UP-VLC, 2012-2017). This brought Harald Haas in as a partner and also Dominic O'Brien's group at Oxford, the Ian White/Richard Penty group at Cambridge, and colleagues at St Andrews working on fast response organic color converting materials (organic semiconductors). The basic conception of UP-VLC was what may be called 'data through display' – the idea that not only were micro-LEDs capable of very high modulation and data rates individually, but they can also be readily deployed in high-density 1-D and 2-D arrays permitting new forms of spatial modulation and spatial multiplexing for visible wavelength optical communications. This program was successful. Major achievements included using orthogonal frequency-division multiplexing (OFDM) to demonstrate multi-Gb/s data rates for the first time from a single micro-LED; multi-Gb/s multiple-input-multiple-output (MIMO) systems with arrayed micro-LED sources and multi-pixel detectors; wavelength division multiplexing (WDM) of multiple micro-LEDs of different colors and/or down-converted using a variety of fast-response color converters. As well as optical wireless applications, we also explored polymer optical fibre and polymer waveguide guided wave optical communications with micro-LEDs. Overall, these results were very timely and may be said to have inaugurated a sub-field of micro-LEDs which has now taken off dramatically worldwide – some of the publications have already amassed several hundred citations each. We summarized much of this in a review article in 2017 in the journal Semiconductor Science and Technology.

LED professional: What is the current status of micro-LEDs for optical wireless communications?

Prof. Martin DAWSON: As described above, we very consciously took the approach that micro-LEDs would only become mainstream if they used mass-market epistructures, and so have concentrated throughout on processing c-plane sapphire grown GaN LED material of commercial standard and also GaN-on-Si of commercial grade. Optimising the pixel layout and processing of these devices has allowed individual micro-LEDs to show modulation bandwidths ≈1GHz and data rates of up to ≈10Gb/s, so these are now established as serious optical communications components, despite (or arguably because of) their inherent simplicity.

Our group and a number of other groups around the world have been exploring new wavelengths for the devices. For example, micro-LEDs in the deep ultraviolet (DUV) are very interesting for both line-of-sight and non-line-of-sight optical wireless data links, and modulation and data rate performance in the DUV is beginning to approach that of longer-wavelength micro-LEDs. The DUV is fascinating because such wavelengths in atmosphere can scatter around objects over 10's to 100's meter distances and also DUV light is in the solar blind region of the spectrum. Recently we have combined three separate ultraviolet wavelength micro-LEDs into a wavelength division multiplexing demonstration which achieved 10Gb/s data rates in the ultraviolet.

As these new wavelengths and capabilities continue to be demonstrated, new applications scenarios are emerging. Polymer optical fibre (POF) guided wave communication is one important area. There is also underwater wireless optical communication. Both of these applications take advantage of the fact that the wavelengths of micro-LEDs can correspond to low-loss transmission windows in the medium. We have also begun to look at micro-LEDs for communication between satellites. Laser-based systems work well for such applications, but are bulky, power-hungry and generally require sophisticated collimation and beam-steering optics. Taking advantage of the correspondence between the operating wavelengths of micro-LEDs

Figure 9: Part of the Institute of Photonics cleanroom showing ICP dry etching tools essential for micro-LED research.

Figure 10: The Technology and Innovation Centre (TIC) at the University of Strathclyde, home to both the Institute of Photonics and the Fraunhofer Centre for Applied Photonics.

and the spectral region of high detection sensitivity for SPADs, we have shown that micro-LED based communications in space at useful data rates should be possible over distances of 10's and potentially 100's km, whilst being of suitably low size, weight and power (SWaP) for ready deployment. This may see particular application in clusters of cube-satellites.

LED professional: What do you see as the major trends in micro-LEDs?

Prof. Martin DAWSON: Clearly the display industry is the main mass-market commercial focus for the technology right now, and this is very exciting indeed. A very large range of innovative companies, from new start-ups to major multinationals, are pressing forward very quickly in addressing the associated manufacturing, scaling and performance challenges. Well-informed market analysis companies are tracking and predicting these trends and commercial priorities very well, and it looks as though smartwatches, consumer television, consumer augmented reality (AR) headsets/glasses, smartphones and automotive applications are among the main themes to keep an eye on. Industry is clearly in the driving seat for such displays now and it will be fascinating in the next few years to see how and when these forms of the technology roll out and where they find market traction.

My colleague, Harald Haas, has argued for a number of years that solid-state lighting and data communications are converging. What we feel our micro-LED investigations have shown is that there are prospective technological convergences more broadly between displays, communications, lighting and even sensing systems, all based on micro-LED technology. We are fortunate that so much commercial effort is going into display applications of micro-LEDs and some of these broader applications can potentially 'piggy back' on that as the display technology matures.

When industry takes up a new technology and really commits to it, their progress can be very rapid and this always creates a dilemma for academic groups working in the field. There are certainly important underpinning explorations related to display applications that continue to need the novelty and investigative input that academic research can provide, but it is probably wise for academics to seek new applications for, and/or radically new forms of, the device technology.

Digital light projection (DLP) and its range of applications is one such important area of opportunity. The intimate and sophisticated electronic interfacing possible to micro-LEDs, combined with the fast response and high-brightness, spectrally-selective output of the micro-LED devices themselves, offers a wide range of exciting possibilities here. Under the EPSRC-funded program 'Quantic' we have recently developed, along with our University of Edinburgh colleague Robert Henderson, a custom CMOS chip which individually controls the pixels in a 128 x 128 (30 µm micro-LED pixels on a 50 µm pitch) micro-LED array DLP demonstrator in various advanced modes of operation. This includes Megahertz frame rate operation which can also be implemented with pulsed output down to a few nanoseconds. There are very broad implications from this, in areas as diverse as scientific instrumentation, optical camera communications, multi-modal ranging and imaging systems, and optically-based tracking and navigation systems.

LED professional: What will be the status of micro-LEDs in five to ten years from now?

Prof. Martin DAWSON: In five to ten years we will have mass market availability of micro-LED displays in various forms and affordable prices. I think that will include wearable type technology, the AR type products, another important application because of the brightness, the compactness, and efficiency. Maybe TV type markets as well, and huge displays with very high resolutions.

From the displays perspective I think I see the progression of those trends and I can't see anything stopping that, really. The question is to what extent the other areas that we've been looking at over the years, the LiFi, the scientific instrumentation markets and so on, become commercial. For example, you can make little biological diagnostic chips that involve microfluidic channels, micro-LED arrays, photon counting detectors and do this all in a very integrated way. You can project patterns to process exposed photoresist as part of a mask-free direct writing lithographic capability as part of sophisticated semiconductor processing tools. The LiFi capabilities of micro-LEDs may be taken up and use by the polymer optical fiber community is another aspect. I'm optimistic that a number of these applications and products will emerge to real commercialization. That's the scientist's view, anyway!

LED professional: What's your personal view, your emotions, passion and feelings, when looking at the achievements of the past 20 years?

Prof. Martin DAWSON: As researchers we do what we do for fun really. It's just out of curiosity and you have an internal passion or drive to explore something. Our story with micro-LEDs was exactly that; we thought it was an interesting and a fun thing to look at and explore. What's surprised me, as time has gone on, is how rich the vision seems to be. You have one particular picture in mind – say that micro-LED technology might be used for a visible light communications and then you realize there's another aspect: that it might be used for brain/computer interfacing or direct write photolithography or something like that. As soon as one vision reaches a certain level of maturity something else comes up. It's a very rich technology area and that richness continues.

Coming back to your question about how I feel. I'm very happy and thrilled by the fact that I've been involved in something that may actually be a real mass market technology. It would be wonderful to go into the shops at some stage and point a micro-LED product out to my son and say, "You know, I had something to do with that". It would be fantastic to maybe have a micro-LED TV in the house too – who knows? Of course, if achieving a really impactful outcome happens to any researcher, it's really exciting. I think what I've tried to do throughout is just to keep my feet on the ground though and be very aware of the random chance elements in any story of commercial success from research.

I'm not alone in contributing to this technology, of course. I would particularly like to mention my respect for Professor Hongxing Jiang and Professor Jingyu Lin. They got the ball rolling. They wrote the first two or three papers that really started the field.

LED professional: Do you have any final reflections on the journey you have travelled with micro-LEDs?

Prof. Martin DAWSON: That's a very interesting question – thank you. Clearly micro-LED technology is promising enough now that those of us involved from the beginning can claim a share of the credit. It was certainly a risky research area to devote time to in the early 2000's and even through to the mid-2010's: it could easily have lost momentum and gone nowhere. However it does show that it is important to be adventurous in research and take calculated risks, especially at an early/mid stage in your career. We were also fortunate that the attention of the bulk of the gallium nitride research community and of industry was concentrated on other things at the time – conventional chip size LEDs and laser diodes, primarily. We all look to tell our success stories retrospectively, but the reality is that there are never any guarantees, especially in terms of commercial importance – a senior colleague once said that markets for technology are 'unfathomable', and you really can't predict what will happen.

If you are fortunate, as we were in this case, you can stumble on a new multipurpose technology. Micro-LEDs are really exactly that, and in some ways the technology has acted as a kind of 'research torch or flashlight' pointing the way into new fields and new investigations. Another colleague once told me to 'listen to what the technology is telling you'. All I can say is that we have listened as carefully as we could and we continue to do so.

I should say finally that research collaboration has been central to everything we have achieved in this field. In particular, academic colleagues with leading expertise in areas including device physics, CMOS, data encoding and communication protocols, bioinstrumentation, the chemistry, materials science and device applications of organic and inorganic semiconductors, soft and hard matter processing, have made major contributions. Our research funders (mainly EPSRC) have been enlightened enough throughout to offer flexible funding platforms permitting such a multi-disciplinary approach to take place.

For those seeking a fuller exploration of or briefing on micro-LED technology, there have been a number of relevant review articles and book chapters. These include our own reviews in Semiconductor Science and Technology (2017) and Phil. Trans. R. Soc A (2020) and book chapters in Volume 106 of Semiconductors and Semimetals (2021) - the latter volume edited by Hongxing Jiang and Jingyu Lin. Among many others, I also particularly recommend Z. Chen et al.'s review paper in J.Phys.D: Appl. Phys. in 2021.

LED professional: Thank you very much for taking us through this exciting journey about micro-LEDs and your fantastic research work in this field.

Prof. Martin DAWSON: I wish to thank LED Professional for the opportunity to give this interview. ■

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Daylighting & Artificial Lighting for Humboldt Forum in Berlin

Lichtvision Design

Berlin's new Humboldt Forum combines art, culture, science and education. For this purpose, Lichtvision Design has developed a holistic lighting concept that includes façade lighting, daylighting and artificial lighting solutions and even the smallest luminous spots in the showcases. The light emphasises the building's architecture and enables flexible use of it. In the foyer, called the Agora, coffered skylights play with daylight. In the exhibition areas on the other hand, a shading system allows a high degree of flexibility in use: two hangings create different light transmissions. In the Workshops, which are work and event spaces that can be used flexibly, the focus was on recognisability in the lighting concept and subtle routing. At selected locations, visually present luminaires create structure. The Berlin based specialists also planned the lighting for various permanent and temporary exhibitions, such as "Spuren" (traces). The exhibits on the history of the Stadtschloss (city palace), which are distributed throughout the building, open up new perspectives together with the lighting concept.

The Humboldt Forum in Berlin extends over more than 83,000 square metres on the Spree Island. It unites important cultural institutions in a unique centre for art and culture, science and education. During the more than ten-year construction phase, the lighting experts from Lichtvision Design created a holistic lighting design that encompasses almost all areas.

Holistic lighting design throughout the building

From the lighting of the exterior and courtyard façades, visible from afar, to daylighting design and artificial lighting in public, event, and exhibition areas – every luminous spot features design art from Lichtvision. Even in the showcases containing exhibits of the Berlin State Museums. The lighting designers' aim was to integrate light and luminaires seamlessly into the architecture to bring the building and its use to the fore. This starts with the façade: Lichtvision's lighting design immerses the building in a uniform light, as favoured by the client. Instead of emphasising individual elements of the historicising façade, the light accentuates the volume of the Humboldt Forum without distracting the viewer's eye with details.

Transparency meets daylight

The historicising façade also played a role in the daylight planning, as it is reflected in the contemporary foyer, the so called Agora, with its ceiling of windows. In this area, transparency was the defining design element. The main focus was on the dome of the building visible through the glass roof and the three-dimensional façade facing the atrium, which is modelled by direct daylight input. Thanks to the special glazing of the coffered skylights, the lighting designers achieved the best possible lighting quality with high colour rendering and low energy transmission. In addition to transparency, another important planning requirement for the interior was the greatest possible flexibility for users. In the exhibition areas, a special shading system ensures that curators can always create the right light for their visions: Two hangings arranged in the space between the box-type windows allow four different daylight situations. The fabric on the outside darkens the room by reflection while the interior solar protection curtain avoids shadows.

Artificial lighting in public and exhibition areas

In the Workshops, right in the heart of the site, flexibility is brought to perfection: The approximately 1,000 square metre area can be used for various purposes and offers space for workshops or for creating art. In this part of the Humboldt Forum the lighting tools were used in a reduced way by Lichtvision. The designers focused on recognisability in the lighting concept and created a subtle wayfinding. Only at selected locations do luminaires specifically structure the space as visually present objects. The lighting system in the Workshops consists of a combination of diffuse light lines and swivelling spotlights mounted on recessed ceiling tracks to compensate for the low ceiling height. In the large hall and the vestibule, where the ceiling heights reach greater dimensions, a luminous ceiling and ceiling luminaires provide the appropriate light, while in the Forum Café reflective floor luminaires set exciting points of contrast to the straight-lined and simple interior.

Searching for traces with light

Scattered in the Schlosskeller (palace basement) and throughout the building, 35 traces in the exhibition "Spuren" recall important events from the past of the place where the Humboldt Forum stands today. The unexpected locations of the traces, together with the luminous spots planned by Lichtvision down to the smallest detail, open up new perspectives. In this way, the holistic lighting concept by Lichtvision Design accompanies guests on their search for traces and on each individual step through the new Humboldt Forum.

Typology: Museum / Public
Scope of Work: Daylighting, Artificial Lighting & Controls
Completion: Summer 2022
Location: Berlin, Germany
Size (GFA): 83 000 m^2 (Exteriors ≈ 7000 m^2)

Client: Bundesamt für Bauwesen und Raumordnung (BBR), Stiftung Humboldt Forum im Berliner Schloss
Project Lead: Lichtvision Design; Dr. Thomas Müller
Architect: Franco Stella
Photographer: © Florian Selig

Project Link:
https://www.lichtvision.com/projects/museums-cultural-instiutions/humboldt-forum-berlin-germany.html

http://www.lichtvision.com

LICHTVISION DESIGN

The glazing of the coffered skylights was chosen in such a way that optimal light quality can be achieved. In the summer months, an external horizontal shade supports the sun protection of the glazing.


HUMBOLDT
BERLIN
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Cuboid light objects set the central stairwell in the right light.


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ORNAMENTO

The daylit forum, called the Agora, is supported by coffered skylights placed underneath the open ceiling.


1702 / Gesprengt im Herbst 1950
28. April 2016 durch INGA MAREN OTTO

View over the Schlüterhof to Portal 5, which takes you to Deutscher Dom (German Cathedral) and Museumsinsel (Museum Island).

How CSA Group's Lighting Center of Excellence is Helping to Test a Brighter Future for Horticulture

KC Fletcher, Manager of CSA Group's Lighting Center of Excellence in Irvine, California

As a physicist, I've always been interested in understanding the things we can't see with the naked eye. From electromagnets to thermodynamics to wavelengths of light, we are impacted by things we can't see, and I have a passion for learning more about how we can harness their power so we can mitigate their negative effects and increase their benefits. This led me to the field of lighting, where through my work with CSA Group, I've experienced advancements in horticulture lighting, including the introduction of more scientific methods of testing.

When I first began to learn about and test horticultural lighting, most information was passed down anecdotally through "green thumbs" who learned through experiments and practical experience, such as what wavelengths to apply when and for how long. But since then, we have seen science-based methods supporting traditional ones; for example, I have seen horticultural lighting go from high pressure sodium lighting, which wasted energy through heat and acoustic vibrations, turn into energy efficient LED lighting with great light intensity. This has helped to expand the abilities of horticulture, giving the grower more control.

Industry Growth and Opportunities

Technological advancements in horticulture lighting are not just unlocking the potential of crops, they're also allowing the horticultural industry to grow faster than ever. With new companies and products entering the market, there is an opportunity for further education about light testing and certification focused on safety and performance.

Similar to other products and industries, growers now have more control over the tunability of their environment. They are now able to control factors like humidity, temperature, lighting as well as water and nutrition dosing with the touch of a finger. This is helping to unleash the potential of horticulture, as many growers are no longer constrained by geography, weather, or time of day.

Growers no longer must rely only on the lessons passed down through their peers or trial and error. With precision, they can now fine tune the color and wavelengths needed to help the plant absorb and utilize various nutrients. This helps to stimulate their photoreceptors to produce higher quality fruits, vegetables, and flowers.

New State-of-the-art Testing Facility

To address the needs of lighting manufacturers, including those servicing the horticulture industry, CSA Group's Lighting Center of Excellence in Irvine California opened its doors in late 2021. The new state-of-the-art facility centralizes our comprehensive testing and technical expertise under one roof. The new Center of Excellence provides a detailed suite of services including OSHA NRTL safety testing and certification services; photometric performance testing including LM-79, horticultural performance testing and IES file generation; photobiological performance and safety testing; and acoustic testing.

Situated in Southern California, the international hub of the lighting industry, the location of CSA Group's Center of Excellence was strategically selected for the convenience of customers across North America. By consolidating many testing capabilities into our new lab, we can now streamline evaluation services to make the process easier for organizations looking to enter the fast-growing horticulture industry.

Advanced Testing for Safety and Efficiency

To ensure the safety of lighting products, we perform ANSI/CAN/UL 8800:2019 and UL 1598 (CSA C22.2 NO. 250.0:21) tests to check electrical, temperature, rain, humidity, dielectric, ground bond and strain relief to help test a product's safety. This is critical because wavelengths and photons are outside of the human eye response, so they don't provoke an aversion reflex. This is helping businesses keep workers safe as they are now better informed to source quality PPE to prevent invisible, yet harmful side effects like 'purple headaches' due to exposure.

We have invested heavily in our labs outfitting them with advanced equipment for testing. This new advanced technology available at our Center of Excellence is helping with performance and safety testing, as well as identification of efficiency gains.

For example, by testing near-field distribution, we are starting to address the limitation of previous tests which only focused

CSA Group's office and laboratories in Irvine, California.

on far-field distribution. New technological advances are also able to find substantial efficiency gains in LEDs. Compared to high pressure sodium light sources, these new LEDs are energy efficient, producing more intense lighting without wasting watts on heat or sound.

Likewise, through IES file generation we are helping designers of horticultural spaces place their lighting sources appropriately and ensure crops can get both near- and far-field distribution of their lighting sources.

The Future is Bright

CSA Group's testing, inspection and certification of horticulture lighting is not only helping to promote a safe future of horticulture, but an efficient one as well. This will help reduce the carbon footprint of horticulture through more efficient electricity consumption. It also allows horticulture to be adopted in countries where electricity prices are higher, and farming may be more difficult.

I'm also seeing that the benefits of horticultural science are impacting local environments. For example, crop growers have depended on fertilizers to promote growth which can lead to soil contamination, water pollution and aggravation of plant physiological diseases; however, using the right type of horticultural lighting with targeted wavelengths, they can now increase nutrient use and reduce dependency on these fertilizers.

These light systems can also extend production seasons so we can enjoy fresh fruit and vegetables even in the dead of winter. This helps to limit the traveling distance of imported crops which also helps to reduce our carbon footprint.

With the rise in popularity of house plants, we are now seeing a more unexpected group entering the field of horticulture, home growers. The use of horticultural lighting has now entered the home, allowing general consumers to grow flowers and fresh herbs all year round. Which places an increased need on the importance of education, awareness, and safety.

As I look to the bright future of horticultural lighting, I'm excited to be part of the team testing its benefits, possibilities, and safety. When I reflect on the state of the industry just a decade ago, this growth seems incredible, like lettuce from Finland or Canadian avocados. ■

Recommendations for Daytime, Evening, and Nighttime Indoor Light Exposure to Best Support Physiology, Sleep, and Wakefulness in Healthy Adults

Timothy M. BROWN, George C. BRAINARD, Christian CAJOCHEN, Charles A. CZEISLER, John P. HANIFIN, Steven W. LOCKLEY, Robert J. LUCAS, Mirjam MÜNCH, John B. O'HAGAN, Stuart N. PEIRSON, Luke L. A. PRICE, Till ROENNEBERG, Luc J. M. SCHLANGEN, Debra J. SKENE, Manuel SPITSCHAN, Céline VETTER, Phyllis C. ZEE, Kenneth P. WRIGHT Jr

Ocular light exposure has important influences on human health and well-being through modulation of circadian rhythms and sleep, as well as neuroendocrine and cognitive functions. Prevailing patterns of light exposure do not optimally engage these actions for many individuals, but advances in our understanding of the underpinning mechanisms and emerging lighting technologies now present opportunities to adjust lighting to promote optimal physical and mental health and performance. A newly developed, international standard provides a SI-compliant way of quantifying the influence of light on the intrinsically photosensitive, melanopsin-expressing, retinal neurons that mediate these effects. The present report provides recommendations for lighting, based on an expert scientific consensus and expressed in an easily measured quantity (melanopic equivalent daylight illuminance (melaponic EDI)) defined within this standard. The recommendations are supported by detailed analysis of the sensitivity of human circadian, neuroendocrine, and alerting responses to ocular light and provide a straightforward framework to inform lighting design and practice.

Introduction

Besides supporting visual perception, ocular light exposure influences many aspects of human physiology and behaviour, including circadian rhythms, sleep, and alertness (both via circadian system–dependent and circadian system–independent routes), mood, neuroendocrine, and cognitive functions (reviewed in [1–4]). This array of retinally driven responses to light (collectively termed "non–image-forming" or, as used here for brevity, "nonvisual") are important determinants of health, well-being, and performance, and some are already clinically relevant, as evidenced by current light therapy for circadian rhythm sleep disorders and various forms of depression [5–7]. Industrialization and urbanization have progressively and dramatically altered individuals' light exposures, resulting in less light, including natural light, during the daytime and less darkness during the night, due to spending more time indoors where electric lighting provides the dominant source of illumination. Substantial evidence indicates that such altered light exposure patterns (and associated circadian/sleep disruption) contribute to negative impacts on health, sleep, and productivity, ranging from acute increases in accident risk to increased incidence of cardiometabolic disorders and forms of cancer (reviewed in [8–14]). Therefore, there is an urgent need for evidence-led recommendations to help inform the design and application of light emission technologies and human light exposures.

To date, a key challenge when optimizing light exposure for promoting human health, well-being, and performance has been the lack of an accepted scientific framework upon which to quantify the propensity for light to elicit the relevant responses and from which to base recommendations for lighting design and practice. Fortunately, as a result of several decades of scientific advances, research-based recommendations are now possible.

Building on initial observations that physiological responses to ocular light exposure can persist even in people who are totally visually blind [15–17], convergent evidence from studies of humans and animals has shown that such nonvisual responses (including effects on the circadian system, melatonin secretion, sleep/alertness, and pupil constriction) originate via a specialized class of retinal neurons, the intrinsically photosensitive retinal ganglion cells (ipRGCs) [18–26]. The light-sensing photopigment within the ipRGCs is melanopsin, which, in humans, is maximally sensitive to photons in a distinct portion of the visible spectrum to the cone photopigments ($\lambda_{max} \approx$ 480 nm before accounting for filtering through the lens and ocular media) [23,25,27]. As a result, the established photometric quantities used to describe brightness and luminous sensation as perceived by humans do not adequately reflect the spectral sensitivity of any melanopsin-dependent responses to light. Measures such as photopic (il)luminance, which primarily reflect the spectral sensitivity of long and medium wavelength sensitive cones, place substantially greater weight on longer wavelengths than those to which melanopsin is most sensitive. These measures therefore provide an inappropriate surrogate for quantifying the propensity of light to engage ipRGC-driven circadian, neuroendocrine, and neurobehavioral responses (**Figure 1**A).

While the potential value of a melanopsin-based photometric quantity has been recognised for some time, there has also been uncertainty as to whether this provides a sufficiently detailed model of the spectral sensitivity of human ipRGC-driven responses to ocular light exposure [28]. Hence, while the spectral sensitivity of physiological responses to light in visually blind people and animals matches that expected for melanopsin [20,23,25,29], in the fully intact retina, ipRGCs can also receive signals originating from rods and/or cones [26]. Moreover, available data indicate that the relative contributions of melanopsin and rod/cone photoreception to nonvisual ocular light responses, and consequently their apparent sensitivity, may vary as a function of exposure duration, light intensity, and perhaps time of day and/or prior light exposure [25,28,30–33].

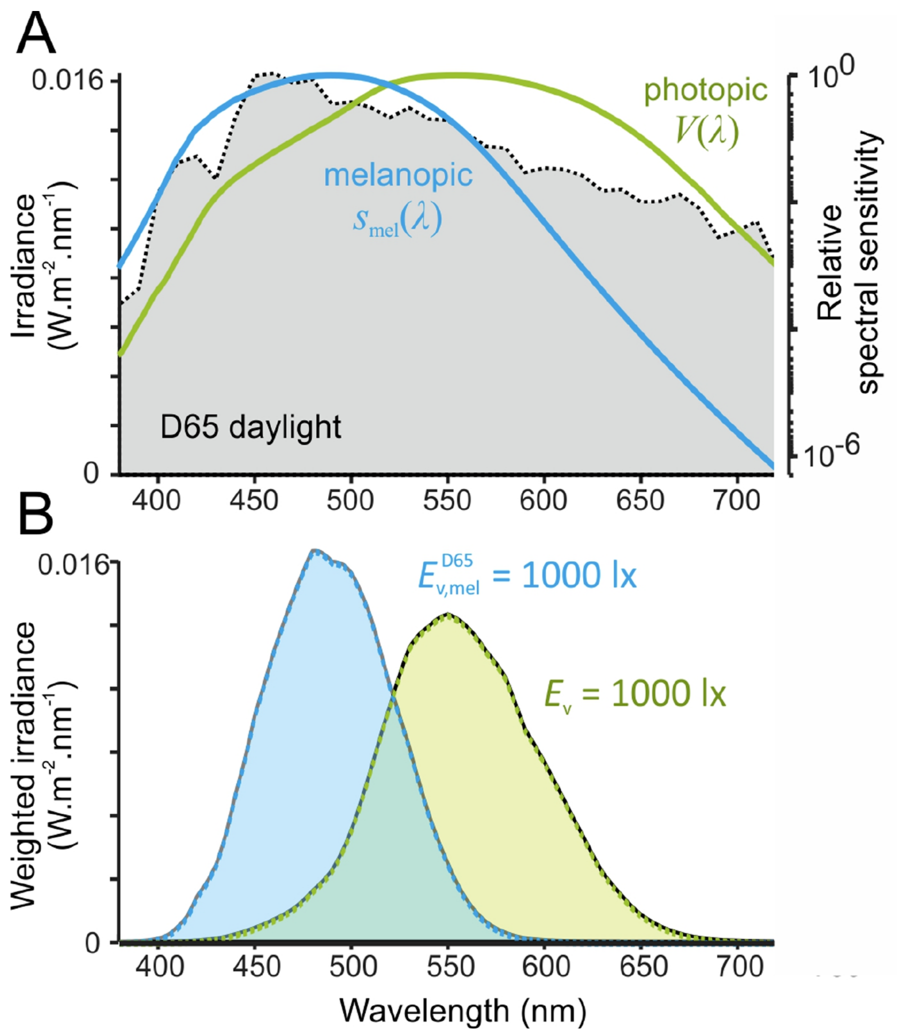

Figure 1: **Differences in photopic and melanopic spectral sensitivity formalized in the SI-compliant system for quantifying ipRGC-influenced responses to light.**
Panel **A** illustrates the melanopic action spectrum (smel(□) with peak sensitivity at 490 nm, following prereceptoral filtering appropriate for a 32-year-old observer) and the photopic (2° spectral luminous efficiency) function, V(□), superimposed on the spectral power distribution of standard daylight (CIE illuminant D65 [142]). Spectral sensitivities are plotted in logarithmic coordinates. Panel **B** illustrates the weighted spectral power distribution for spectrum in **A** multiplied by the photopic and melanopic efficiency functions at 1,000 lux for illuminance (Ev) and melanopic EDI (). Sensitivity curves in **A** are plotted from the tabulated values provided in the CIE S026 standard [34], with weighted irradiance (plots in **B** and associated calculations) derived using the procedures described in detail therein. CIE, Commission Internationale de l'Eclairage; ipRGC, intrinsically photosensitive retinal ganglion cell; melaponic EDI, melanopic equivalent daylight illuminance.

As an initial response to the absence of a suitable metric for quantifying ipRGC-dependent ocular light responses, in 2013, an expert working group proposed a system that weighted irradiance according to the effective in vivo spectral sensitivity of the 5 known human retinal opsin proteins (melanopsin, rhodopsin, S-, M-, and L-cone opsin) [28]. This framework has now been formalized into an international standard with a SI-compliant system of metrology for ipRGC-influenced responses to light (Commission Internationale de l'Eclairage (CIE) S 026 [34]). Within this system, the effective rates of photon capture for each of the human retinal opsins under a given light condition are equated to the photopic properties (e.g., illuminance) of a standard 6500 K (D65) daylight spectrum that would produce the same rate of photon capture. This approach defines, for each opsin class, the α-opic equivalent daylight illuminance (EDI; where α-opic denotes one of the 5 human opsin classes that can contribute to ipRGC-influenced responses, e.g., melanopic; **Figure 1**B). Despite the significant advance provided by this new light measurement standard, to date, explicit scientific consensus guidance on the relationship between the 5 α-opic quantities and the magnitude of practically relevant ipRGC-dependent responses is lacking. For example, how should signals from melanopsin, cones, and rods be weighted? Do these weightings change with light exposure duration and history? What levels of α-opic EDI are appropriate in a given time of day and setting?

Importantly, as originally envisaged [28], adoption of the new measurement approach has facilitated a number of large-scale retrospective evaluations of historical data [35–39] and informed new hypothesis-driven investigations [40–43] on the photoreceptive physiology for circadian, neuroendocrine, and neurobehavioral responses in humans. In total, the evidence from such studies [35–43] supports the view that, under most practically relevant situations (extended exposures to polychromatic light in the absence of pharmacological pupil dilation), light sensitivity of human physiological responses can be reliably approximated by the α-opic irradiance for melanopsin or the corresponding EDI (melanopic EDI). Moreover, based on the consistency of melanopic irradiance–response relationships across studies [38], it is now possible to define realistic, evidence-based recommendations for light exposures that target nonvisual responses (**Figure 2**). Alongside the emergence of freely available tools to calculate the relevant metrics [44,45], there now exists an easily measured and internationally accepted SI-compliant system of metrology [34] to inform lighting design and associated policy.

Here, we describe expert consensus-based recommendations for daytime, evening, and nighttime light exposure, considerations associated with their applicability, the supporting scientific evidence, and any caveats associated with the recommendations as they stand.

Methodology

The Second International Workshop on Circadian and Neurophysiological Photometry in 2019 brought together experts in lighting, neurophysiological photometry and sleep, and circadian research (all workshop participants are included as authors of this manuscript). The workshop was chaired by Brown and Wright who invited participants based on professional and/or academic qualifications and on reputation of being a leading expert in the field, including being an author of key scientific publications and/or international standards on the topic. Workshop participants were provided goals and key questions to address prior to a structured face-to-face meeting. The primary focus of the meeting was to develop expert consensus recommendations for healthy daytime and evening/nighttime light environments tentatively based on the new SI-compliant measurement system (CIE S 026:2018) [34]. Initial questions for review and discussion were the following:

1. What range of melanopic EDI can be reasonably considered to provide minimal and maximal impacts on nonvisual ocular light responses in humans?
2. Do signals from rods and/or cones also play a major role, and, if so, what relevant guideline levels could be recommended to account for such actions?
3. Do the answers to (1) and/or (2) vary across different nonvisual forming responses (e.g., circadian entrainment/resetting, sleep/arousal, effects on hormone secretion, and mood) and, if so, what is the most appropriate general recommendation that can be provided?

Participants were also asked to consider if recommended light exposures would vary depending on which specific biological effects one is trying to achieve and/or on the target population (e.g., shift workers, specific clinical applications, etc.) and to include empirical literature supporting their views. In the face-to-face meeting, the morning of the first day was devoted to detailed presentations and discussion of the relevant scientific literature, and the afternoon was devoted to breakout sessions for discussion of questions 1 to 3 noted above. The second day was devoted to further discussion with sufficient time to address all opinions, ideas, and concerns. Voting to determine the expert consensus recommendations occurred via an iterative process; voting was limited to workshop participants and, where consensus could not be initially reached, discussion and review of the relevant literature resumed until participants were in agreement. Following the establishment of the expert consensus recommendations, a writing plan was formulated to produce the current paper. Subgroups of workshop participants initially drafted sections of the manuscript most relevant to their specialist expertise, including providing accounts of the scientific evidence from laboratory and field studies, relevance to other existing visual standards, and other special considerations associated with application of the recommendations. The workshop chairs (Brown and Wright) then integrated the expert content into a complete draft manuscript, including the recommendations formalized during the meeting. Workshop participants reviewed, edited, and approved both the draft (available as a preprint [46]), and this

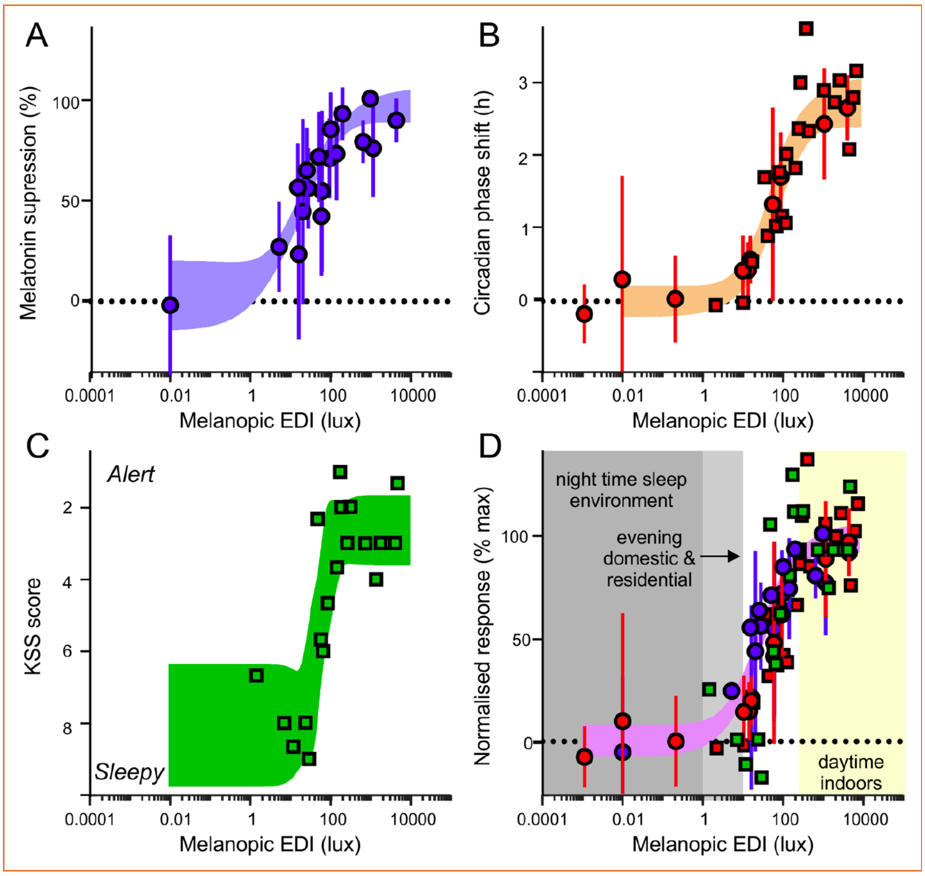

Figure 2: **Recommendations for melanopic light exposures in relation to the sensitivity of melatonin suppression, circadian phase resetting, and subjective alerting responses.**
Data are derived from laboratory studies (in humans without the use of pupil dilators) investigating the impact of long exposures (>2 hours) to primarily broadband light sources on melatonin suppression [69,88,95,143,144] (**A**), circadian phase resetting [83,89,143,144] (**B**), and subjective alerting responses [86] (**C**), as analysed in [38]. Group data (round symbols) are presented as mean ± SD; otherwise, data for individual subjects are presented (square symbols). Shading represents the 95% confidence limits of an unconstrained 4-parameter sigmoid fit to the data. For comparison across different response types (**D**), data sets from **A–C** were normalized relative to the range of the curve fit for that response type. Shaded areas in **D** reflect the consensus recommendations of the Second International Workshop on Circadian and Neurophysiological Photometry for sleep, evening, and indoor daytime environments. Recommendations are intended to provide realistic targets that minimize inappropriate nonvisual responses in the sleep environment (melanopic EDI <1 lux) and reduce these so far as is practically possible presleep (3 hours before habitual sleep; melanopic EDI <10 lux) while maximizing relevant effects across the intervening daytime hours (melanopic EDI >250 lux). The nonshaded region indicates the range of melanopic EDI that should, where possible, be avoided during evening and nighttime and are considered suboptimal for daytime environments. EDI, equivalent daylight illuminance.

final version, which provides additional rationale supporting the recommendations and their practical application. The recommendations and associated considerations described herein are therefore the product of a workshop involving the authors. We are aware that such a workshop can rarely be exhaustive with respect to expertise and/or views across all potential stakeholders.

Expert Consensus-based Recommendations

The recommendations, described below, are intended to provide realistic targets that will result in appropriate circadian, neuroendocrine, and neurobehavioral responses to ocular light exposure in humans.

Daytime Light Recommendations for Indoor Environments

Throughout the daytime, the recommended minimum melanopic EDI is 250 lux at the eye measured in the vertical plane at approximately 1.2 m height (i.e., vertical illuminance at eye level when seated). If available, daylight should be used in the first instance to meet these levels. If additional electric lighting is required, the polychromatic white light should ideally have a spectrum that, like natural daylight, is enriched in shorter wavelengths close to the peak of the melanopic action spectrum (**Figure 1**A).

Evening Light Recommendations for Residential and Other Indoor Environments

During the evening, starting at least 3 hours before bedtime, the recommended maximum melanopic EDI is 10 lux measured at the eye in the vertical plane approximately 1.2 m height. To help achieve this, where possible, the white light should have a spectrum depleted in short wavelengths close to the peak of the melanopic action spectrum.

Nighttime Light Recommendations for the Sleep Environment

The sleep environment should be as dark as possible. The recommended maximum ambient melanopic EDI is 1 lux measured at the eye.

In case certain activities during the nighttime require vision, the recommended maximum melanopic EDI is 10 lux measured at the eye in the vertical plane at approximately 1.2 m height.

Additional Considerations

i. Exposure to a stable and regular daily light–dark cycle is also likely to reinforce good alignment of circadian rhythms, which may further benefit sleep, cognition, and health. These recommendations should therefore be applied at the same time each day, so far as possible.
ii. These recommendations are not intended to supersede existing guidelines relating to visual function and safety. The nonvisual ocular light responses covered here should be an additional level of consideration provided that relevant visual standards can still be met.
iii. These recommendations are derived based on data from (and intended to apply to) healthy adults (aged 18 to 55) with regular daytime schedules. Special considerations may apply to specific populations (e.g., children, older people, shift workers, or other individuals whose light sensitivity deviates substantially from an "average" healthy adult) as discussed later in this publication (see "Special cases and exceptions").

Relationship to Existing Standards

There are several national and international standards that are relevant to indoor light exposure in the built environment, which have been developed under rigorous due processes, consensus, and other criteria. In terms of biological safety, there is a recent recommended practice for photobiological safety that provides guidance on ocular and dermal health relative to light exposure from all varieties of indoor lamps and lamp systems (American National Standards Institute/Illuminating Engineering Society (ANSI/IES) RP-27-20) [47]. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has also released a recent statement concerning photobiological safety, specifically of light exposure from LEDs [48]. Other existing guidelines, codes, and specifications for lighting installations in indoor places primarily concentrate on visual function, including visual comfort, visual performance, and seeing safely for people with normal, or corrected to normal, vision.

Current specifications within lighting practice are based on illuminance and several additional qualitative and quantitative needs concerning glare, color rendering, flicker and temporal light modulation, luminance distribution, and the directionality and variability (of both color and level) of light. These specifications are crafted to enable people to perform their visual tasks accurately and efficiently, even for difficult circumstances or extended durations (e.g., Deutsches Institut für Normung (DIN) SPEC 67600 [49]; ANSI/IES RP-28-16 [50]; and EN 12464–1 [51]). Together with the focus on energy saving, the existing guidelines restrict the illuminance indoors to levels that are typically at least 1 order of magnitude below the natural light environment outdoors. Moreover, the electrical light sources in most common use, while optimized for their visual qualities, are typically substantially less efficient at stimulating melanopsin than natural daylight of equivalent illuminance, i.e., the light they provide has a low ratio of melanopic EDI to photopic illuminance (quantified by the melanopic daylight efficacy ratio (melanopic DER) [34,52]; see **Figure 3**). This leaves us with an indoor light environment that is potentially suboptimal for supporting human health, performance, and well-being [9–12,53]. For example, Comité Européen de Normalisation (CEN) guidelines specify a minimum task plane photopic illuminance of 500 lux for writing, typing, reading, and data processing tasks. When just meeting this illuminance threshold with regular lighting (i.e., melanopic DER well below 1; **Figure 3**A and **Figure 3**B), typical (vertical) melanopic EDIs encountered across the working day will fall below 200 lux (e.g., [54–56]). Moreover, specified illuminance levels for other settings, where visual demands are lower (e.g., corridors, rest rooms, etc.), will typically be substantially lower than the above (melanopic EDI <200 lux; [51]).

This publication is centrally based on an internationally balloted standard from the CIE [34], which now provides an accepted framework upon which to derive lighting specifications that optimize visual, circadian, neuroendocrine, and neurobehavioral responses to light. The corresponding expert-led consensus recommendations for biologically appropriate lighting are reflected in general melanopic EDI thresholds for various times of day/night. The recommendations presented here are intended to be widely achievable within the constraints of other relevant lighting guidelines (e.g., via lighting of appropriate spectral composition; **Figure 3**C and **Figure 3**D) and to provide a sound scientific basis for the formal development of recommended practices in light and lighting from national and international standards organizations (e.g., ANSI, CIE, DIN, IES, and the International Organization for Standardization; ISO).

In closing this section, we note that a number of other recommendations relevant to physiological and neurobehavioral effects of light have been proposed in recent years, including some guidelines and specifications by commercial (for-profit) entities (reviewed in [57]). Unlike these previous suggestions, the present recommendations are both built around an SI-complaint, internationally accepted and validated measurement system and are supported by expert scientific consensus, features recognised as critical by established industry regulatory and standardization bodies [58,59].

Practical Considerations

As noted above, while the recommendations detailed here are expected to be widely achievable, implementing these in any real-world setting necessitates care not to compromise other important regulations and/or considerations (e.g., visual appearance, glare, thermal comfort, safety, and energy efficiency). For example, an important consideration in achieving our recommendations for daytime settings is whether this would necessitate higher overall light levels and therefore increase energy expenditure and/or the risk of visual discomfort (e.g., glare). Notably, there is a range of approaches that (individually or in combination) could allow these recommendations to be met while avoiding such issues, including increasing the availability and accessibility of natural daylight (e.g., [56]), engineering the spectral content of electric lighting to increase melanopic DER, adjusting finishes and furnishings to optimize surface reflectances, and adjusting the placement, angular dispersion and size of accessible luminous surfaces to enhance vertical illuminances and/or minimize glare [60–64].

As an illustration of the above, a recent study modelling common office and educational settings found a combination of adjustments in surface finishes and spectral composition of lighting could readily produce 2- to 3-fold changes in vertical melanopsin-weighted light exposure [62]. For the conditions assessed there, where relevant national standards specified horizontal illuminances of 300–400 lux, achieving an average melanopic EDI of 250 lux in the vertical plane required an approximately 50% increase in horizontal illuminance and energy output when using an 'off-the shelf' tuneable white LED (6500 K; melanopic DER = 0.83). With appropriate design, however, color mixed LEDs can allow much higher melanopic DERs, even when maintaining warmer color temperatures (e.g., up to 1.4 for 4000 K sources [61]). Moreover, engineered LED luminaires that balance less extreme increases in melanopic DER with a good fidelity color rendition index and slightly cooler white light [65] can facilitate meeting our daytime recommendations without significantly compromising energy expenditure or visual qualities (e.g., **Figure 3**D). Further, the energy efficiency of color-mixed LED sources is rapidly approaching that typical of standard phosphor-converted LEDs and is scheduled to exceed this over the next decade [66]. Thus, while optimizing building and lighting design to maximize energy efficiency and minimize visual discomfort remain important goals, these should not ultimately prove impediments to implementing our recommendations in most settings.

By contrast, increased energy expendi-

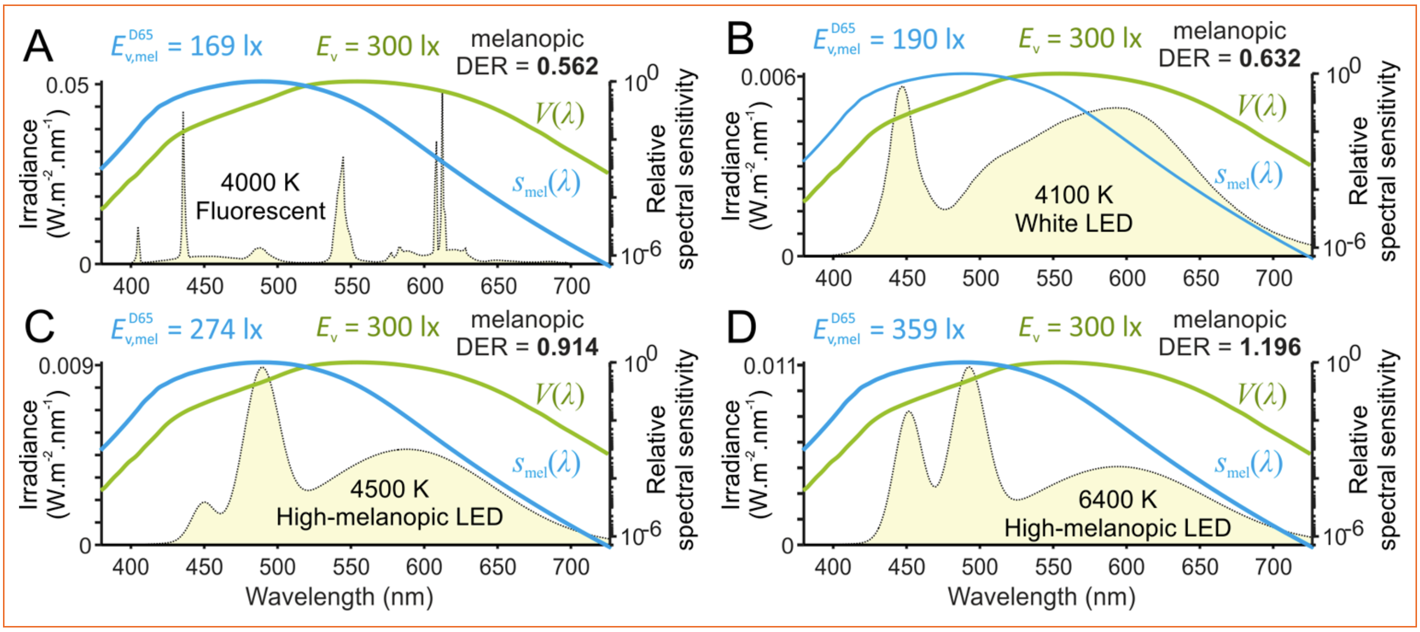

Figure 3: **Impact of divergent spectral composition of electrical white light sources on melanopic efficiency.**
Panels **A** and **B** illustrate spectral power distributions (yellow) for commonly encountered fluorescent (**A**) and LED-based (**B**) white light sources. Panels **C** and **D** represent high melanopic content LED source of similar (**C**) and cooler (higher) correlated color temperature (**D**) achievable with current technologies. Spectra in **A** and **B** represent CIE standard illuminants F11 and LED-B1, plotted from tabulated source data [142], spectra in **C** and **D** were modelled by combining weighted combinations of spectra from commercially available broad and narrowband LED sources. Melanopic (blue; V(□)) and photopic (green; V(□)) spectral efficiency functions are shown for reference. Photopic illuminance (Ev) and melanopic equivalent daylight (D65) illuminance () for each spectrum is provided above, along with the melanopic efficiency for that light source (melanopic daylight (D65) efficacy ratio; melanopic DER, defined as the ratio of melanopic irradiances for this source to that for a D65 light source at the same photopic illuminance [34,52]). Note, in this example, all sources provide a photopic illuminance of 300 lux, but vary in melanopic EDI, due to the relatively low melanopic DER of commonly used white light sources. CIE, Commission Internationale de l'Eclairage; melanopic DER, melanopic daylight efficacy ratio; melaponic EDI, melanopic equivalent daylight illuminance.

ture is not a concern with respect to our evening/nighttime recommendations, where the significant practical consideration is rather ensuring that there is sufficient light to comfortably and safely perform visually guided activities. For the sleep environment, it is already natural to greatly minimize light exposure (by turning off lights, covering windows, and the like). There is likely still a fair proportion of individuals for whom the sleep environment is currently slightly above a melanopic EDI of 1 lux (e.g., [67,68]), although we would not envisage any significant barriers to reducing this where required (e.g., via use of blackout blinds and the installation of orientation lighting where needed). Outside of the sleep environment, however, ensuring sufficient light is available for vision is of course essential.

From existing ambulatory field assessments, evening (photopic) illuminance is commonly reported in the order of 30 lux [69–73]. Although certain rooms (e.g., kitchens) may be more brightly lit, this value of 30 lux corresponds to vertical illuminances typically measured in most indoor domestic environments in the evening [74]. In such cases, meeting the threshold melanopic EDI of 10 lux need not require any significant change in overall illuminance. Hence, many commonly used domestic warm white (2700 K to 3000 K) LEDs already have a melanopic DER sufficiently low (<0.35 [52]) to meet our target while maintaining an illuminance of approximately 30 lux. Consistent with this view, a recent study that assessed evening light exposure in home settings via wearable spectrophotometers found that in nearly 50% of occasions melanopic EDI was already at or below 10 lux [75]. Moreover, many cases where evening light exposure was above this level involved lighting enriched in shorter wavelengths and could, in principle, been brought in line with our recommendations simply by using lower melanopic DER light sources. Further, the use of appropriate task lighting and/or lighting specifically engineered to minimize melanopic output (e.g., [69]) may further support activities that benefit from illuminances above 30 lux while maintaining an overall environment where melanopic EDI at the eyes remains below 10 lux (although the latter ultra-low melanopic DER sources will likely come at the expense of reduced color discrimination). A particular challenge, however, comes from indoor environments outside the home (e.g., spaces shared by individuals with radically different daily/work schedules), where existing visual standards will often specify illuminance levels (>100 lux) that cannot be achieved while maintaining a vertical melanopic EDI <10 lux and optimal color discrimination.

Nonetheless, while meeting our evening target may not be achievable in all instances, it should be broadly achievable in most domestic settings with currently available lighting technology and, therefore, for those with the regular daytime work schedules for which it is intended to apply.

A final point for consideration relates to the likely benefits of implementing our recommendations that may have to be weighed up to justify any associated costs (e.g., due to upgrading workplace lighting). As discussed in detail below, there is certainly evidence that increased daytime light can improve subjective or objective measures of performance, sleep, alertness, and/or mood and that decreased evening and nighttime exposures can reduce adverse effects of light on sleep, circadian rhythms, and long-term health (see “Evidence from real-world settings”). Directly quantifying the benefits that might be expected associated with implementing our recommendations is far more challenging. In the future, large-scale longitudinal studies that combine data on objectively measured performance (e.g., sick days, productivity, and incidence of accidents), health outcomes, and appropriately measured (personal) light exposure may provide such information. In the interim, it is worth noting that, even ignoring possible impacts on the incidence of common and costly health complications associated with circadian disruption (e.g., cardiovascular disease, diabetes, and cancer), benefits associated with improved sleep alone could potentially be substantial [76]. Indeed, insufficient sleep is estimated to cost the United States 2.4% GDP, due to absenteeism, accidents, reduced productivity, etc. [76,77]. Moreover, even comparatively modest improvements for those with poor sleep (<6 hours sleep-/night increased to 6 to 7 hours/night) are predicted to increase US GDP in the order 1.7% or approximately 300 billion USD/year [77].

Scientific Rationale

Evidence from Laboratory Studies

The rationale for basing these recommendations upon melanopic EDI is, in the first instance, provided by a comprehensive analysis of data aggregated from controlled laboratory studies (performed in healthy adults aged 18 to 55) that have evaluated the 2 best understood neuroendocrine and circadian light responses in humans: acute suppression of nocturnal pineal melatonin production and circadian phase resetting by evening or nighttime light exposure [36–39]. Those data indicate that, for a wide range of monochromatic, narrowband and broadband light sources and exposure durations, such ocular light responses are better predicted by melanopic irradiance than by photopic illuminance or other existing metrics. Additional contributions from photoreceptors other than melanopsin are expected based on known ipRGC biology [26,28], and evidence for such contributions has been observed under certain circumstances [30,78,79]. Importantly, however, the sum of empirical human data suggest that any such influences are sufficiently limited that, under most practically relevant circumstances, the spectral sensitivity of circadian and neuroendocrine and, by extension, other related nonvisual responses to ocular light exposure, can be well approximated by melanopic EDI.

The clearest evidence for contributions from photoreceptors other than melanopsin has so far come from evaluations of melatonin suppression in short (<1 hour) time windows following exposures to monochromatic light in participants with dilated pupils (to remove indirect effects of pupil constriction on apparent sensitivity). Data from two such studies are compatible with the possibilities that S-cones [78] or the photopic system [30] may contribute alongside melanopsin (see also reanalysis in [79]). Importantly, however, a large body of data with and without use of pupil dilation indicates that for exposures of an hour or more, melatonin suppression can be reliably predicted by melanopic EDI [37,38,80,81]. This conclusion is further strengthened by findings from recent studies that have employed photoreceptor isolating stimuli to confirm that melanopsin-selective changes in irradiance modulate melatonin production [40,41] but failed to find any effect of large variations in irradiance selectively targeting S-cones [42]. Further evidence consistent with a dominant role for melanopsin comes from earlier observations that totally blind humans (where remaining light responses match the spectral sensitivity expected for melanopsin) [23,25] can display near-full melatonin suppression [15,17,23], as do individuals with color vision deficiencies [82].

In line with the data discussed above, totally blind individuals can also display circadian phase resetting responses to bright white light of comparable magnitude to sighted individuals [16]. Findings from one study in sighted individuals with pharmacologically dilated pupils are suggestive of cone contributions to circadian phase resetting following long (6.5 hours) exposures to dim monochromatic light [30].

However, an equivalent effect is not readily apparent across data from studies performed on participants with undilated pupils [38,83,84]. Thus, laboratory data collected under conditions that are more relevant to the real world, where pupils are freely light responsive, indicate that the influence of cones is sufficiently small that melanopic irradiance can provide a reliable approximation of the spectral sensitivity of circadian phase resetting.

By contrast to the circadian and neuroendocrine responses discussed above, other relevant effects of light that are of importance but mechanistically less well understood, such as acute light effects on alertness, have not yet received the same degree of analytic and parametric study. Nonetheless, light-dependent changes in subjective alertness have commonly been reported (reviewed in [2,85]) and, where performed, functional studies employing electroencephalogram (EEG) or magnetic resonance imaging approaches reveal clear neurophysiological correlates of such subjectively measured alertness changes (e.g., [43,86,87]).

With respect to the conditions under which such alerting effects occur, a recent comprehensive meta-analysis reveals that self-reported alerting responses to white light are commonly observable within a similar range of light intensities to those associated with effects on the circadian system (irrespective of time of day) [2]. Many of the original studies contributing to the latter analysis predate the discovery of melanopsin. It is possible, however, to obtain reasonable approximations of melanopic EDI from the photopic illuminance reported by earlier studies, by reference to the typical ratio of these 2 parameters expected for the relevant light sources (i.e., melanopic DER). For example, a recent meta-analysis [2] notes a significant subjective alerting effect of bright white light in almost 80% of studies (15 of 19) where the “dim” light condition was below 80 lux and the “bright” condition >500 lux (values that correspond to melanopic EDI of <50 lux and >250 lux, using a conservative melanopic DER of 0.6 and 0.5, respectively). Further, the published irradiance response data for subjective (and objective) alerting responses to nocturnal broadband white light exposure [86] align very well with the relationship between melanopic EDI and circadian-related responses determined from other studies that did not employ pupil dilation [38,88,89] (**Figure 2**).

The recent meta-analysis discussed above [2], which could not reach definitive conclusions regarding spectral sensitivity of alerting responses, did not assess the extent to which the magnitude of alerting responses were predictable based on melanopic EDI. Nonetheless, the most informative studies included in that analysis [69,90–94] and other relevant studies and meta-analyses [36,38,39,69,95] indicate that alerting effects produced by light of varying spectral composition are certainly better predicted by melanopic irradiance than other available metrics. Moreover, recent studies provide evidence that selectively increasing melanopic irradiance, in the absence of changes in either illuminance or color, can promote self-reported alertness during both day [43] and evening [40]. The former study also confirmed EEG correlates of enhanced daytime alertness via alpha attenuation test [43]. Collectively, these data do not exclude the possibility that cone signals might exert a greater influence over acute alerting responses to light than is apparent for circadian and neuroendocrine effects. Nonetheless, the bulk of available evidence supports the view that melanopic EDI is the best currently existing predictor of alerting responses to light and is relevant for both day and evening/nighttime scenarios. The currently available data do not provide any definitive evidence that the sensitivity of such alerting responses differs substantially relative to other melanopsin-driven responses to evening/nighttime light exposure (**Figure 2**) or between night and day (reviewed in [2,85]). Accordingly, in the absence of new information, the sensitivity range defined for the more comprehensively studied circadian and neuroendocrine responses can be used as a sensible predictor of propensity of light to modulate alertness, regardless of time of day.

In sum, most of the available laboratory data suggest that melanopic EDI is a reliable index that provides a good approximation of the apparent spectral sensitivity of human circadian and acute nonvisual responses to ocular light exposure. In particular, for the extended exposures to polychromatic light that are relevant to everyday living environments, existing evidence indicates that any additional contributions from cones (or rods; whose spectral sensitivity is close to melanopsin [34,96,97]) do not compromise the predictive value of melanopic EDI.

As befitting a system evolved to optimize physiology and behaviour in anticipation of day–night transitions driven by the Earth’s rotation relative to the sun, the operating range of human circadian, neuroendocrine, and alerting responses to ocular light exposure spans the range of light intensities typically encountered between civil twilight and sunrise/sunset (i.e., melanopic EDI of approximately 1–1000 lux; **Figure 2**). The recommendations indicated above are therefore intended to ensure that the sleeping environment is kept at a limit below which any appreciable nonvisual responses of this nature are elicited and to minimize negative effects of the light environment during sleep and presleep hours [98]. Similarly, recommendations for daytime and evening light exposure are intended, so far as practically possible, to respectively maximize and minimize any associated effects on sleep, alertness and the circadian system. By providing an appropriately marked day–night signal and reducing potential disruptive effects of evening light, collectively, these recommendations are expected to promote robust and appropriately timed circadian functions in most individuals [99], as well as to promote alertness throughout the day and support healthy sleep.

Also worthy of note here, a number of studies have provided evidence that undesirable effects of evening/nighttime light can be mitigated by brighter light exposure earlier in the day (e.g., [31,33,100–104]). While opposing actions of light exposure during morning/daytime and evening are a well-understood feature of circadian function [105,106], these modulatory effects also extend to more acute actions of evening light, such as its ability to suppress melatonin production. At present, the physiology responsible for such actions are not well understood, nor does currently available data enable a detailed assessment of the intensity and/or time range across which such effects operate. What is clear, however, is that modulatory effects of prior light exposure are certainly not limited to earlier parts of the day [33,104]. Accordingly, such observations suggest a further potential benefit of maintaining high melanopic light exposure throughout the day. The visual requirements necessary or desirable for some activities during later parts of the evening (e.g., relating to illuminance and/or color) place a limit on the extent to which disruptive effects of white light can be entirely avoided simply by reducing melanopic EDI (e.g., using lighting with a lower melanopic DER). Higher levels of daytime light exposure may therefore help mitigate any disruptive effects associated with unavoidable light exposure in later parts of the evening.

Evidence from Real-world Settings

While our current understanding of the spectral sensitivity and dynamic range of circadian, neuroendocrine, and neurobehavioral light responses in humans is most directly informed by laboratory studies, our recommendations are also supported by field evaluations of the impact of environmental lighting.

Access to electric lighting is associated with reduced daytime and increased nighttime light exposure and altered sleep timing [107–110], with many individuals in modern society routinely experiencing melanopic EDI <250 lux during the day, especially those with delayed sleep schedules [72,73]. Accordingly, there have been a number of real-world studies implementing daytime high melanopic lighting interventions in workplaces, schools, and care homes that provide practical corroboration for the recommendation outlined above [111]. Such practically focused investigations were not designed to evaluate melanopsin contributions per se (with increases in melanopic EDI usually being accompanied by increases in color temperature and/or illuminance), but such studies do provide valuable insight in likely real-world benefits associated with meeting our recommendations.

In offices, increasing the melanopic output of architectural lighting (approximately 2-fold) via short wavelength-enriched lamps (17 000 K; melanopic DER ≈1, versus 3000 K to 4000 K; melanopic DER<0.6) had beneficial effects on self-reported alertness, performance, mood, and sleep quality [54,55]. Similarly, enhancing daytime melanopic exposure by increased access to natural daylight in the workplace improved sleep and objectively measured cognitive performance (higher-order decision-making) in office workers [56]. In these studies [54–56], the average melanopic EDI in the control working environment was <150 lux (standard 3000 K to 4000 K fluorescent lighting; **Figure** 3A), with the experimental "active" conditions increasing melanopic EDI to approximately 170–290 lux. Hence, modest and readily achievable adjustments to increase light exposure can be associated with measurable benefits, without any observable detrimental effects.

In schools, findings from a series of studies employing fluorescent lighting with various intensities and spectra indicate that settings with a higher melanopic output (melanopic EDI >500 lux) can improve measures of concentration and reading comprehension compared to current standard lighting (typically providing melanopic EDI <200 lux; [112–115]). Similar benefits of short wavelength-enriched (17 000 K) versus standard 4000 K fluorescent light on reducing sleepiness have also been shown in college-aged students during afternoon lectures [116]. Further, building on seminal work showing the benefits of increased daytime light levels for the elderly [117], several clinical trials have shown the benefits of enhanced melanopic light exposure during daytime hours on care home residents [118–120]. There is evidence of reduced circadian sensitivity/responsiveness to light in older adults (see "Special cases and exceptions"), including changes in lens transmission that could reduce effective retinal dose corresponding to a given melanopic EDI by approximately 50% relative to the (young) standard observer on which calculations are based [44]. Nonetheless, in these studies, compared to control conditions (typical daytime melanopic EDI <150 lux), implementation of higher melanopic, short-wavelength enriched, polychromatic lighting (5500 K to 17 000 K, providing melanopic EDI >250 lx) led to a range of improvements including reduced depression, agitation, and anxiety, better daytime activity and, in some studies, improved sleep quality.

Collectively, increasing melanopic light exposure during the day in line with our recommendations has been shown to benefit alertness, performance, and sleep in a wide range of real-world settings, even in the presence of daylight or stimulants such as caffeine or for younger or older age groups. Further, there is minimal evidence for negative effects of increased daytime melanopic light exposures. One care home study [120], where the brightest daytime light intervention was examined (bright 17 000 K lighting providing melanopic EDI approximately 900 lux), reported a reduction in sleep efficiency and quality when compared to standard 4000 K lighting (melanopic EDI approximately 100 lux). Further, in an office study of dayworkers where the melanopic EDI of control condition was already high (approximately 400 lux) further increases (melanopic EDI approximately 750 lux) associated with the use of an 8000 K lighting system appeared to prevent the normal seasonal advance in sleep timing [121]. While the latter could be considered beneficial, as it enhances circadian alignment to the working day, long-term effects of decoupling from seasonal environmental rhythms is, to date, unclear. Given these data, future research is warranted to identify the potential beneficial and adverse effects on human physiology, cognition, behaviour, and health of electric lighting that greatly exceeds our intensity recommendations.

In addition to reduced daytime light exposure, increased exposure to electric light in the evening and night is commonly considered to exert adverse effects on sleep, circadian rhythms, and health outcomes [8–11,67,68,122]. Indeed, even relatively low levels of light in the sleep environment (conservatively, melanopic EDI >3 lux) have been associated with impaired sleep and increased incidence of diabetes in large cohort studies [67,68]. Further, typical evening light levels often fall within the range where significant nonvisual responses would be predicted from laboratory studies [75]. For example, a significant source of evening light exposure is from visual displays, which in the absence of any other illumination, can provide melanopic EDI of >60 lux [52,123,124] (above the typical level of exposure required to produce half-maximal subjective alerting, melatonin suppressing, and circadian phase shifting responses in laboratory studies; **Figure** 2). Indeed, several studies have shown that light from modern visual displays is sufficient to reduce the evening rise in melatonin, impair sleepiness, and/or increase subjectively or objectively measured alertness [123–126]. Moreover, manipulations that reduce exposure to short wavelength light from such displays has, in some laboratory studies, been found to lessen these effects [125,126] as have selective reductions in melanopic output [40]. There have not yet been large-scale longitudinal field studies on how effective such manipulations might be, although it is noteworthy that the reductions in melanopic radiance achievable simply by adjusting the spectral content of current visual displays are modest (approximately 50% decrease). As such, we expect that such approaches will be most beneficial when combined with other strategies to minimize evening illumination (e.g., dimming of screens and low melanopic ambient lighting). In addition, the potential protective role of adequate daytime light exposure to attenuate adverse effects of evening and nighttime light exposure on circadian physiology requires future research.

Special Cases and Exceptions

While the current recommendations are intended to be widely applicable, the scientific underpinnings primarily derive from studies of neuroendocrine, circadian, sleep, and alerting responses to ocular light exposure in healthy young adults. Even among this group, findings from a recent laboratory study show significant (>10-fold) interindividual variations in sensitivity to white light–induced suppression of the evening rise in melatonin [88]. The physiology underlying this variability is currently unknown. Importantly, however, assuming such variability is indicative of that for the healthy adult populations contributing across the range of lab studies discussed above, it is inherently incorporated into our recommendations. Hence, targets for daytime and nighttime exposures are based on light intensities found to produce near maximal or minimal responses across the test population. With respect to the recommendation for evening settings, there may be more significant variability in the relative magnitude of circadian, neuroendocrine, and associated neurophysiological responses, based on the intraindividual differences noted above [88]. In the absence of any ready means for predicting individual differences in sensitivity, the present recommendation of a maximum melanopic EDI of 10 lux is intended to appropriately minimize undesirable effects of evening light for the "average" healthy adult while allowing for sufficient light for common evening activities (see "Practical considerations" for further discussion). As it stands, where the evening light environment currently results in a melanopic EDI above 10 lux, reducing exposure in line with our recommendations is certainly still expected to be beneficial, regardless of individual differences in sensitivity, although future developments may make it possible to refine recommendations for specific individuals.

The magnitude of circadian and neuroendocrine responses to light also depends on age, with those in young children being larger and those in older adults tending to be smaller when compared to young adults [127–131]. These observations may, in part, reflect age-related differences in the amount of light reaching the retina (due to changes in pupil size and lens transmittance), although more direct changes in sensitivity or amplitude may also be involved. Certainly, one previous study that investigated the impact of age-related changes in lens transmittance did not find that this was associated with the expected reduction in light induced melatonin suppression in older adults [132]. Changes in light exposure in line with the current recommendations are still expected to be of general benefit to both young [112–115,124,126] and older individuals [67,68,118–120] (where their current daytime light exposure falls below, or evening/nighttime exposure above, the relevant targets). Select groups, however, may further benefit from higher daytime (e.g., older people) and/or lower evening exposures (e.g., children) than indicated in the recommendations. Similarly, disruptions to sleep and circadian rhythms are commonly associated with many disorders and disease states [8,133]. While adjusting light exposure may be of benefit in some or all of these conditions, further research will be required to determine whether alterations to the recommended thresholds will be required for such individuals.

In addition to the points above, a particular challenge in optimizing light exposure to benefit health and performance relates to shift workers. Current light exposure advice for night shift workers is still not mature [134], and we want to stress that the present recommendations are not intended for this purpose. There is certainly evidence that increasing melanopic light levels in the work environment can improve subjective and/or objectively measured alertness and performance in shift workers [135–138]. Important benefits such as these do, however, need to be weighed in the context of potential disruptions to circadian alignment and chronic effects on health [8–14]. Addressing these important questions remains a key area for future investigation and shift work–related consensus guidance on best practice.

As discussed above, it is also essential that any changes to light exposure intended to adjust melanopsin-dependent physiological responses do not compromise visual requirements. For example, the elderly may need brighter lighting than recommended above to move safely between the bedroom and bathroom at night [12]. In many cases, such issues may be addressed by using lighting with an appropriate spectral composition (i.e., by using lighting with a low melanopic DER) and/or lighting designs that avoid direct illumination of the eyes. Nonetheless, there may be some instances where meeting the requirements for visual performance, visual comfort, and safety are incompatible with our recommendations regarding nonvisual responses, in which case the former must take precedence. Finally, while it is possible to comply with the recommended melanopic EDI thresholds specified here solely via exposure to electric light, there are a number of known and suspected benefits of exposure to broad-spectrum, outdoor, daylight [53,139–141].

Future Directions

The recommendations outlined here are derived from a synthesis of several decades of research into the biology regulating circadian, sleep, physiological and cognitive responses to light and their practical implications. There is, without question, evidence that the use of melanopic irradiance as a model for the spectral sensitivity of such responses represents a simplification of the underlying biology. Although, as an aside, we note that this is true also for the established and widely used, photometric quantities (luminance and illuminance) that are currently applied to quantify conventional "brightness." Nevertheless, we leave open the possibility that a deeper understanding of rod and/or cone contributions to physiological responses will reveal multi-photoreceptor models of spectral sensitivity that may allow a more accurate prediction of circadian, sleep, neuroendocrine, and/or cognitive responses. The contribution of rods to such responses is an interesting topic for research in its own right. Nonetheless, including a rod component in any such future metrics is unlikely to substantially improve the accuracy with which they recreate the spectral sensitivity of the relevant response(s), since the very similar spectral sensitivity profiles of rods and melanopsin render effective irradiance for these 2 opsins highly correlated [97]. Conversely, cone spectral sensitivity is quite distinct from melanopsin and has the potential to substantially refine metrics for circadian and neurophysiological responses. In particular, future work may reveal specific lighting conditions that maximize cone influence to produce practically relevant modulations in nonvisual responses to light (e.g., on the circadian system, neuroendocrine function, sleep physiology, and/or and alerting responses). At present, however, existing evidence indicates that the use of melanopic irradiance/EDI would not lead one to substantially over- or underestimate biological and behavioral effects for the types of light exposure that are typically encountered across daily life [35–38,40–43].

Further research into the factors influencing individual differences in the sensitivity of melanopsin-mediated responses to light exposure may make it possible to tailor guidelines to specific groups or even individuals. For the time being, our recommendations are derived from group data that must incorporate much of this variability. As such, it is expected that the recommendations for daytime and the sleep environment should be broadly applicable and strongly engage relevant circadian and neurophysiological responses for the vast majority of healthy adults. Known, age-related sources of variability are already at least partly accounted for by the inclusion of corrections for changes in lens transmission described in the nonnormative appendices of the existing standard [34]. Recommendations may, however, be modified in the future for certain groups such as children, older adults, or patient groups whose sensitivity to light may differ from the healthy adult population on which the present recommendations are based.

The current recommendations are intended to inform lighting design considerations for typical, real-world environments such as offices and other workplaces, schools, and colleges, residences, care homes, and in- and outpatient settings. As noted above, application of our recommendations across such settings is facilitated by the free availability of tools for calculating melanopic EDI (and also estimating this given known illuminance and type of lighting) [44,45]. Nonetheless, the emergence of low-cost commercial sensors for direct measurement of melanopic EDI (akin to conventional "lux meters") is expected to further increase the ease with which the recommendations can be adopted.

A final point for consideration relates to applications of light therapy for clinical conditions like affective and circadian rhythm sleep disorders or for purposes such as improving circadian regulation and alertness in night and shift workers or transmeridian travellers experiencing jet lag. The current recommendations are not directly formulated for such uses, but the existing applications of ocular light therapy likely involve the same or similar biological underpinnings as discussed above. Given existing evidence for benefits of bright light therapy [5–7], perhaps widespread adoption of the recommendations described here will contribute to a reduction in the prevalence of affective and sleep disorders. More significantly, however, we expect the scientific framework that informs these recommendations to provide a concrete basis upon which to generate hypotheses to test for the subsequent establishment of optimal light treatment recommendations for clinical and travel applications. ■

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Abbreviations: ANSI, American National Standards Institute; CEN, Comité Européen de Normalisation; CIE, Commission Internationale de l'Eclairage; DIN, Deutsches Institut für Normung; EEG, electroencephalogram; ICNIRP, International Commission on Non-Ionizing Radiation Protection; IES, Illuminating Engineering Society; ipRGC, intrinsically photosensitive retinal ganglion cell; ISO, International Organization for Standardization; melanopic DER, melanopic daylight efficacy ratio; melaponic EDI, melanopic equivalent daylight illuminance

Citation: Brown TM, Brainard GC, Cajochen C, Czeisler CA, Hanifin JP, Lockley SW, et al. (2022) Recommendations for daytime, evening, and nighttime indoor light exposure to best support physiology, sleep, and wakefulness in healthy adults. PLoS Biol 20(3): e3001571. https://doi.org/10.1371/journal.pbio.3001571

Funding: The 2nd International Workshop on Circadian and Neurophysiological Photometry (2019) was funded by the Biotechnology and Biological Sciences Research Council (UK) grant BB/N014901/1 to TMB and RJL, with additional contributions from the University of Manchester Centre for Biological Timing and the Neuroscience and Mental Health Domain. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: I have read the journal's policy and the authors of this manuscript have the following competing interests: GCB was supported, in part, by DOE grant DE- EE0008207, NAS Award #HR 05-23 UNIT 905; NASA grant NNX15AC14G; the NSF ERC LESA Center; BIOS, Toshiba Materials Science, The Nova Institute (The Institute for Integrative Health) and the Philadelphia Section of the Illuminating Engineering Society. GCB reports having issued (USPTO 7,678,140 and 8,366,755) and pending (USPTO 16/252,300, 15/085,522 and 14/273,971) patents related to the photoreceptor system for melatonin regulation. That intellectual property has been licensed by Litebook Company Ltd. He has been a paid consultant by Lutron, Inc., and McCullough Hill LLC. In addition, he and his research program have received financial, material and travel support from a range of federal, industrial, legal and philanthropic organizations in the past and present. CC has received consulting, honoraria, travel, accommodation and/or subsistence fees for invited keynote lectures, conference presentations or teaching from Toshiba Materials, Velux, Firalux, Lighting Europe, Electrosuisse, Novartis, Roche, Elite, Servier, and WIR Bank. CC is a member of the Daylight Academy. CAC reports grants to BWH from FAA, NHLBI, NIA, NIOSH, NASA, and DOD; is/was a paid consultant to AARP (2018), American Academy of Dental Sleep Medicine (2017, 2018), Eisenhower Medical Center (2018), Emory University (2019), Ganésco, Inc. (2017), Inselspital Bern (2019), Institute of Digital Media and Child Development (2017, 2018, 2019), Klarman Family Foundation (2017, 2018, 2019), M. Davis and Co (2018), Physician's Seal (2019), Samsung (2016), Sleep Research Society Foundation (2019), State of Washington Board of Pilotage Commissioners (2018), Tencent Holdings Ltd (2019), Teva Pharma Australia (2019, 2020), UC San Diego (2018), University of Michigan (2017), University of Washington (2017, 2018), and Vanda Pharmaceuticals Inc (2017, 2018, 2019, 2020), in which CAC also holds an equity interest; received travel support from Annenberg Center for Health Sciences at Eisenhower (2018), Aspen Brain Institute (2018), Bloomage International Investment Group, Inc. (2018, 2019), UK Biotechnology and Biological Sciences Research Council (2019), Bouley Botanical (2017, 2018, 2019), Dr. Stanley Ho Medical Development Foundation (2019), European Biological Rhythms Society (2017, 2019), German National Academy of Sciences (Leopoldina) (2019), Illuminating Engineering Society (2018), National Safety Council (2017, 2018, 2019), National Sleep Foundation (2017, 2018, 2019), Society for Research on Biological Rhythms (2018), Sleep Research Society Foundation (2018), Stanford Medical School Alumni Association (2019), Tencent Holdings Ltd (2019), University of Zurich (2018), and Vanda Pharmaceuticals Inc (2017, 2018, 2019), Ludwig-Maximilians-Universität München (2018), National Highway Transportation Safety Administration (2018), Office of Naval Research (2018), Salk Institute for Biological Studies/Fondation Ipsen (2018), The National Academy of Sciences, Engineering, and Medicine (2017), The Wonderful Company (2017), Department of Defense (2017); receives research/education support through BWH from Cephalon, Mary Ann & Stanley Snider via Combined Jewish Philanthropies, Harmony Biosciences LLC (2019, 2020), Jazz Pharmaceuticals PLC Inc (2017, 2018, 2019, 2020), Johnson & Johnson (2019), NeuroCare, Inc. (2019), Philips Respironics Inc/Philips Homecare Solutions (2017, 2 018, 2019, 2020), Regeneron Pharmaceuticals (2018, 2019, 2020), Regional Home Care (2019), Teva Pharmaceuticals Industries Ltd, Sanofi SA, Optum, ResMed, San Francisco Bar Pilots, Sanofi, Schneider, Simmons, Sysco, Philips, Vanda Pharmaceuticals; is/was an expert witness in legal cases, including those involving Advanced Power Technologies, Aegis Chemical Solutions LLC (2019), Amtrak (2019); Casper Sleep Inc (2019), C&J Energy Services (2019), Complete General Construction Co (2017), Dallas Police Association (2019), Enterprise Rent-A-Car (2019), Espinal Trucking/Eagle Transport Group LLC/Steel Warehouse Inc (2017, 2018, 2019), FedEx, Greyhound Lines Inc/Motor Coach Industries/FirstGroup America (2017, 2018, 2019), Pomerado Hospital/Palomar Health District (2017, 2018), PAR Electrical Contractors Inc (2019), Product & Logistics Services LLC/Schlumberger Technology Corp/Gelco Fleet Trust (2019), Puckett Emergency Medical Services LLC (2019), South Carolina Central Railroad Company LLC (2017, 2018), Union Pacific Railroad (2019), United Parcel Service/UPS Ground Freight Inc (2017, 2018), and Vanda Pharmaceuticals (2019, 2020); serves as the incumbent of an endowed professorship provided to Harvard University by Cephalon, Inc.; and receives royalties from McGraw Hill, and Philips Respironics (2017, 2018, 2019, 2020) for the Actiwatch-2 and Actiwatch Spectrum devices. CACs interests were reviewed and are managed by the Brigham and Women's Hospital and Mass General Brigham in accordance with their conflict of interest policies. SWL has received consulting fees from Atlanta Falcons, Atlanta Hawks, BHP Billiton, Delos Living LLC, EyeJust Inc., McCullough Hill Leary PS, Noble Insights, OpTerra Energy Services Inc., Pegasus Capital Advisors, Phillips Lytle LLP, Plan LED, Rec Room, Serrado Capital, Slingshot Insights, Stantec and Team C Racing. He has current consulting contracts with Akili Interactive, Apex 2100 Ltd, Consumer Sleep Solutions, Headwaters Inc., Hintsa Performance AG, KBR Wyle Services, Light Cognitive, Lighting Science Group Corporation/HealthE, Look Optic, Mental Workout/Timeshifter, Paul Weiss Rifkind Wharton & Garrison LLP, Six Senses, and View Inc. SWL has received unrestricted equipment gifts from Bionetics Corporation and F.LUX Software LLC; a fellowship gift from Stockgrand Ltd; has equity in iSLEEP, Pty; royalties from Oxford University Press; honoraria plus travel, accommodation and/or meals for invited seminars, conference presentations or teaching from Estée Lauder, Ineos, Informa Exhibitions, MIT, Roxbury Latin School, and Teague; travel, accommodation and/or meals only (no honoraria) for invited seminars, conference presentations, teaching or editorial duties from DIN, Emory University, Lightfair, SLTBR, Solemma and Wiley. SWL has an ongoing investigator-initiated grant from F. Lux Software LLC and a Clinical Research Support Agreement from Vanda Pharmaceuticals Inc. SWL holds a process patent for 'Systems and methods for determining and/or controlling sleep quality', which is assigned to the Brigham and Women's Hospital per Hospital policy, and 'Method and system for generating and providing notifications for a circadian shift protocol' held by Mental Workout Inc. SWL has served as a paid expert in legal proceedings related to light, health and work patterns. SWL was the Program Leader for 'Safety and Productivity Improvements' in the CRC for Alertness, Safety and Productivity from 2015-2019, through a part-time Adjunct Professor appointment at Monash University, Australia. SWL's interests are reviewed and managed by Brigham and Women's Hospital and Partners HealthCare in accordance with their conflict of interest policies. RJL and TMB have received research funding from Signify (formerly Philips Lighting). RJL has received speaker fees from Samsung. RJL, LP, LJMS and MS have served as members of the CIE Joint Technical Committee 9 on the definition of CIE S 026:2018. These were unpaid roles. JPH was supported, in part, by DOE grant DE- EE0008207, NAS Award #HR 05-23 UNIT 905; NASA grant NNX15AC14G; NSF Award #2037357; Rensselaer Polytechnic Institute; BIOS, Toshiba Materials Science, The Institute for Integrative Health; and the Philadelphia Section of the Illuminating Engineering Society. He has been a paid consultant by Lutron, Inc. and McCullough Hill LLC. MM is an unpaid founding member of the Daylight Academy (DLA). SNP reports no conflicting interests. JOH, In addition to paid employment with Public Health England, is Vice-President Standards of the CIE, a member of the Scientific Expert Group of the International Commission on Non-Ionizing Radiation Protection and a number of their Project Groups, Co-Convenor of an ISO committee on Integrative Lighting, a member of two committees of the Illuminating Engineering Society of North America, Convenor of an IEC committee and a member of a Core Group for the World Health Organization, all as unpaid roles. LP served as the CIE reporter to CIE TN 003:2015 on the first Manchester Workshop in 2013, is currently serving as Director and as Secretary of the CIE Division "Photobiology and Photochemistry", as the CIE reporter on the CIE S 026 Toolbox (doi.org/10.25039/S026.2018.TB), as a member of CIE Joint Technical Committee 14 (working with ISO Joint Working Group 4) on Integrative Lighting, and as the CIE reporter on the second Manchester Workshop 2019 (attended by all the authors), all as unpaid roles LJMS's full time position at Eindhoven University has been partially funded by Signify, he is also active in various unpaid roles within the International Commission on Illumination (CIE). DJS is a co-inventor on issued patents (EP1614441A1 and WO2015052207A1), a Founding member of the Daylight Academy and reports receiving research support from BBSRC and EU H2020-SC1-2020-Two-Stage-RTD, ENLIGHTENme, Innovative policies for improving citizens' health and wellbeing addressing indoor and outdoor lighting (No. 945238). CV is an unpaid member of the Circadian Light Therapy (Inc.) and the Chronsulting Scientific Advisory Boards. In addition, CV's research and scholarship is funded by the University of Colorado Boulder, the Colorado Clinical and Translational Sciences Institute, the National Institutes of Health, and the Department of Energy. MS is currently an unpaid member of CIE Technical Committee TC 1-98 ("A Roadmap Toward Basing CIE Colorimetry on Cone Fundamentals"). MS was an unpaid advisor to the Division Reportership DR 6-45 of Division 3 ("Publication and maintenance of the CIE S026 Toolbox"). Between 2017 and 2020, MS was elected Chair of the Color Technical Group within the Optical Society. Since 2020, MS is an elected member of the Daylight Academy, an unpaid member of the Board of Advisors of the Center for Environmental Therapeutics, and MS is a member of the Technical Advisory Board of Faurecia IRYStec Inc. Over the past two years (2019-2020), MS has received industrial research support from f.lux software LLC, Ocean Insight, and BIOS Lighting. MS reports funding from the Wellcome Trust, the Royal Society, EPSRC, Bioscientifica Trust, Fight for Sight, Freie Akademische Gesellschaft Basel, and the University of Oxford. PCZ reports funding from National Institutes of Health, Eisai, Philips, Jazz Pharmaceuticals, Technogel, Harmony Biosciences, Apnimed, X – a Division of Alphabet, Inc., Merck and Sanofi. In addition, PCZ has patent applications pending (62/038700; 15/517458). KPW reports during the conduct of the 2nd International Workshop and preparation of this manuscript being a board member of the Sleep Research Society; chair of the American Academy of Sleep Medicine Clinical Practice Guideline for the Treatment of Adults with Shift Work Disorder and Jet Lag Disorder Workgroup; receiving research support from the NIH, the Office of Naval Research, the PAC-12 conference, and consulting for Circadian Therapeutics, LTD., Circadian Biotherapies, Inc. Philips Respironics, U.S. Army Medical Research and Materiel Command-Walter Reed Army Institute of Research outside the submitted work.

Why UV-C Technology Needs to be a Standard Feature in Building and Renovation Design

Marion EBEL, Senior Policy Manager and
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UV-C is an established technology used for disinfecting water, air, and surfaces. It's also been proven to deactivate, without exception, all bacteria and viruses against which it has been tested, including those responsible for causing tuberculosis, influenza, the common cold, and SARS, among others. The key to UV-C's effectiveness is its use of a non-visible and higher-energy form of light called Ultraviolet (UV) light. On the electromagnetic spectrum, UV falls somewhere between visible light and x-rays. It is these wavelengths that allow UV-C to destroy the DNA and RNA of pathogens, preventing them from dividing and multiplying and thus essentially rendering them dead. UV-C does not reach the Earth's surface from the sun. Instead, this germicidal energy must be artificially produced through technology – something that humans have been doing since 1910. Although the technology was used to help contain the 1918 flu pandemic, it wasn't until the 1930s that it became widely commercialised and used to fight such diseases as tuberculosis and measles.

Today, of course, UV-C is once again in the news, this time as one of the key defences against COVID-19. Because the SARS-CoV-2 virus, which causes COVID-19, is primarily spread via aerosols, proper indoor ventilation has become of paramount importance. According to the World Health Organisation (WHO), increasing ventilation is the best way to improve air quality.

Although in the past UV-C was primarily used as a means of sanitising surface areas, it can also play a major role in creating equivalent ventilation, also called an Equivalent Air Change per Hour, or eqACH. In general, equivalent ventilation aims to achieve the same level of virus/pollution reduction as can be achieved through ventilation (via opening the windows or HVAC) but by using an alternative technology, such as lamps. More specifically, eqACH occurs when an alternative technology, such as UV-C, inactivates 63% of the active viral pathogens in a room.

To illustrate how UV-C based equivalent ventilation works, take, for example, a typical room in an office. UV-C capable luminaires (discharge lamps, LED emitters, Excimer lamps, etc.) are installed on the walls and ceilings, shining a narrow (invisible) beam of UV-C light just above head height. The air in the room circulates through natural convection, and every time the infected air passes through the UV-C rays, it becomes sanitised before being recirculated through the room. Where low ceilings or smaller rooms make upper air installations impossible, closed UV-C devices can serve as an alternative option. For example, fans can be installed to draw the air towards the luminaires (which are often integrated into ceiling panels), where it is disinfected by UV-C lamps before being recirculated into the room. UV-C lamps can even be installed directly inside HVAC systems, sanitising the air as it travels through the ducts.

Not only do these UV-C disinfection solutions reduce contamination risks, in some cases, it can do so better than mechanical ventilation systems. As a result, buildings using UV-C disinfection have been able to increase occupancy rates and reduce the downtime caused by disinfecting protocols. UV-C technology also has a sustainability benefit over mechanical ventilation, with studies showing that UV-C applications could cut a building's HVAC energy demand in half.

Making UV-C Standard

Because UV-C is an effective, sustainable, and simple method for helping to keep people healthy and safe, LightingEurope believes it should become a standard feature in building and renovation design – and not just during a pandemic. That's because the air inside buildings isn't just full of potential pathogens, it's also full of pollution. In fact, indoor air can be up to five times more polluted than the air outside – and sometimes much more. And considering that we spend up to 90% of our time indoors, this can be a problem.

At the EU level, the European Commission is actively looking for policy options for improving indoor air quality. LightingEurope applauds these initiatives, but stresses the need not only for new policies, but also for optimising existing policy measures.

Take for example the EU Renovation Wave Initiative, which aims to help Europe meet its 2030 and 2050 climate goals by at least doubling the rate of renovation happening across the Continent. This initiative is an opportunity to not only look at the energy efficiency aspect of buildings, but also to ensure a better and safer indoor environment for occupants.

Last December, and as part of the Renovation Wave Initiative, the European Commission published a proposal to revise the Energy Efficiency of Buildings Directive (EPBD) **[??–??]**. LightingEurope believes the importance of disinfection technologies should be recognised in this revision and, in particular, in relation to the specific provisions addressing indoor air quality. Renovation projects must be a priority investment at the national, regional and local level. Each euro invested in renovation must deliver benefits in terms of energy efficiency, smartness, and indoor environmental quality. Likewise, the EU's Occupational Safety and Health (OSH) Strategic Framework for 2021-2027 looks at preventing illnesses and works to prepare for future potential health crisis. Disinfection technologies will be essential to achieving this framework's objectives.

UV-C technologies can also play a role in the Zero Pollution Action Plan, which was adopted by the European Commission on 12 May 2021. Of particular interest to the lighting industry is the plan's annex **[??–??]**, specifically Action 6, which stresses the need to 'assess pathways and policy options to improve indoor air quality, and propose legislative measure as relevant' by 2023.

In addition to our policy work, LightingEurope also collaborates with other organisations in advocating for the creation of a safe indoor environment. As a member of the Global Lighting Association (GLA), we have been at the frontlines of developing important safety guidelines **[??–??]**, some of which have been acknowledge by the IEC as IEC PAS 63313:2021 and can be used by countries for reference in future regulation.

LightingEurope is also working with HVAC associations on indoor environmental quality, with a particular focus on how UV-C disinfection can complement mechanical ventilation to deliver safe, virus-free indoor spaces.

A Sense of Urgency

Ultimately, the COVID-19 pandemic has put the spotlight on the many benefits UV-C disinfection technologies can bring. It has also brought a new sense of urgency to ensuring these technologies become a standard part of our building regulations. Looking ahead, since UV-C technology is proven to inactivate, without exception, all bacteria and viruses against which it has been tested, such devices will also come to play an indispensable role for other major health concerns. This includes antimicrobial resistance (AMR), which is responsible for an estimated annual 33,000 deaths in the EU alone. Leveraging this momentum, LightingEurope has established a UV-C Subgroup, dedicated to advocating for the uptake of quality UV-C disinfection products. To learn more about this important initiative, reach out at `mailto:contact@lightingeurope.org`. ■

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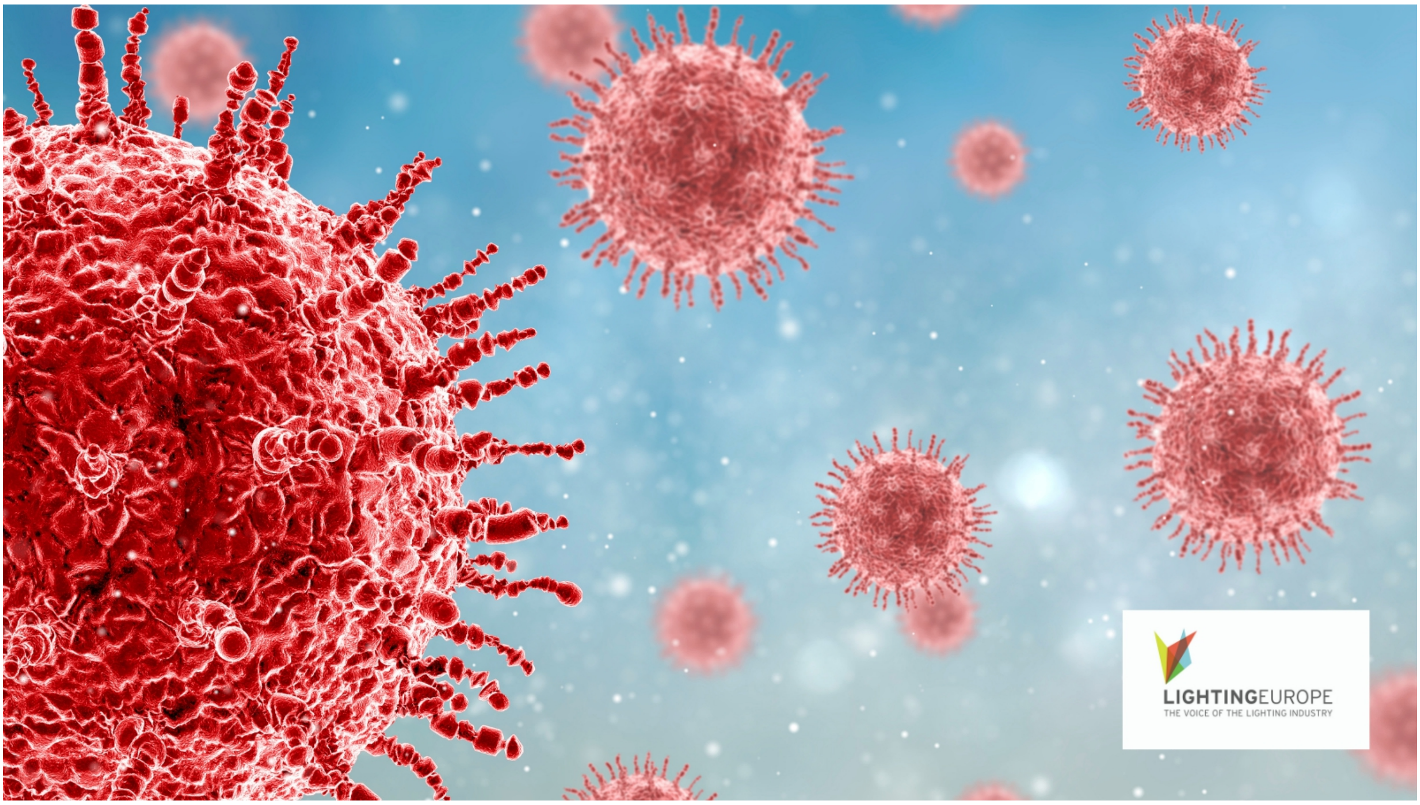
[6] LightingEurope Position Paper on the benefits of using UV-C disinfection to combat COVID-19

[7] Frequently Asked Questions on UV-C Disinfection Technologies



Lamination Process for Flexible Electronics and LED Technology

Volker KOKULA, R&D Manager at Lumitronix

Flexible electronics are becoming increasingly important across the entire industry. Market analyses consistently promise economic growth for this revolutionary type of electronics. More and more groundbreaking new developments are being published, often preceded by many years of research and development work. Today, technical progress allows the integration of innovative concepts of flexible electronics into existing products. This enables the optimization of existing applications, but also the development of completely new product solutions. The automotive industry is considered an important pioneer for innovative technologies. Therefore, flexible electronics were used to make several future-oriented lighting and control concepts as well as new applications in the field of electromobility available in series production.

Flexible boards assembled with components are thinner and lighter than conventional solutions on rigid boards, which is why they save space and contribute to weight and therefore fuel reduction. But the versatility of flexible electronics also opens new opportunities for a wide range of lighting applications. Enormous flexibility and multifunctionality with minimal space requirements, innovative material combinations for PCBs (e.g., paper as PCB) and contemporary design possibilities for multidimensional light installations score points against conventional solutions on rigid PCBs. Flexible electronics enable a technological leap for artificial light and unusual lighting concepts in completely new dimensions.

Practical Problems

Novel manufacturing processes can be used to produce electronic assemblies and components that are noticeably light, thin, and extremely flexible. Unfortunately, problems often arise in practice. If an innovative development concept with the revolutionary nature of electronics is to make it from the initial idea to its implementation in the product, there are several hurdles to overcome.

First, the often technically complex electronic assemblies from the research must be made reliably reproducible in copious quantities for the industry. The path from a prototype to mass production can be tedious if the machine production processes must be repeatedly checked and adjusted if necessary.

An essential criterion for market maturity is the reliability and stability of the electronics. Compared to rigid modules, electronic devices on flexible substrates are quite fragile. They are very susceptible to damage due to the high sensitivity of the functional materials.

Handling problems may already occur during the assembly of the sensitive flexible units in the factory. In addition, various environmental influences can have a negative impact on the electronic components in use.

Proven Protection Methods for Electronics

Flexible materials equipped with different components for light and functionalities require reliable protection for a long service life. The lighting industry uses established technical methods to maintain the functionality of electronics under different operating conditions.

Basically, a distinction can be made between two methods of protection: Conformal coating and potting. Selecting the right type of protection against damaging external factors is difficult because it is an additional cost-relevant process in the production, which entails both strengths and weaknesses depending on the type and implementation. For an optimal result, the desired degree of protection for the electronics must already be kept in mind in the initial phase of design development.

Potting

Potting is the process of enclosing an entire PCB within its housing with liquid materials, often mixtures based on polyurethanes, silicones or epoxies. Potting can be done either manually or with a special machine. A potting compound with a material thickness >1 mm remains permanently as an integral part of the electronic unit. Thus, potting not only protects from external factors, but can also help conceal the intellectual property contained in the electronics.

PROS

- Good chemical resistance (epoxy)
- Good moisture resistance
- High electrical insulation
- High shock and vibration resistance
- High resistance to abrasion

CONS

- Material thickness reduces mechanical flexibility
- Resistance to abrasion may reduce flexibility
- Weight
- Big effect on optical transmission
- Difficult process whose success depends on many influences (humidity, temperature, sterility)

Coating

For the coating, special protective lacquers with a chemical composition often consisting of acrylic, polyurethane, silicone, epoxy or parylene are used. The protective coating with a material thickness <0.2 mm can be applied to the flexible boards using different methods: spray applications, vapour phase, dip applications, manually with brushes, etc. The application can be carried out on the entire assembly or only selectively on the sensitive areas.

PROS

- Mechanical flexibility
- Very low material thickness
- Very low weight
- Little effect on optical transmission

CONS

- Weak chemical resistance
- Low moisture resistance
- Low electrical insulation
- No or little resistance to abrasion

Lamination Process: Strengths of Conventional Protection Methods Combined in a New Technology

Especially new markets and future-oriented applications with flexible PCBs demand high requirements that often cannot be optimally fulfilled with the established potting or coating methods. Depending on the application, a choice has to be made for one of the methods and disadvantageous factors have to be considered.

To enable an optimum of both established protection types, an innovative production process was recently established at the Lumitronix[1] factory to make the flexible electronic units more robust for challenging applications.

[1] https://b2b.lumitronix.com/en/

The Lamination Process Increases Mechanical Resistance

In the production line, flexible printed circuit boards equipped with components are laminated with several polymer materials that serve as a protective layer. Very large areas (W x L: 1 x 1.7 m) can be processed. Virtually "endless" products in a roll-to-roll manufacturing process are also conceivable in the future.

In the lamination process, the special plastic layers are applied to the front and back of the flexible PCB material by applying a high heat (temperature <250°C) and a high, consistent pressure. Depending on the intended use, the combination of the composite materials can be adjusted. The parts mounted on the flexible PCB are encapsulated, excluding almost all air residues in the composite material.

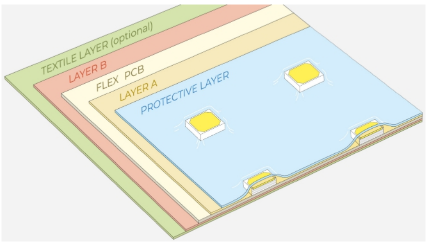


Figure 1: Schematic structure of a laminated LED module

After lamination, the mechanical resistance increases significantly and protects the electronics from physical stress, such as vibrations and shocks. Since only very thin layers are used (<0.6 mm per side), the flexibility of the module is still maintained. Depending on the PCB layout and the assembled components, a minimum bending radius <5 mm after lamination is still possible without causing the module to break.

The lamination can be exposed to temperature fluctuations. The protective layers can withstand continuous operation in an environment with temperatures of up to 120°C. However, electrical interference can also be safely repelled by the protective layers of the lamination. A high surface resistance ($10^{14}/cm^2$) and a high dielectric strength (>1 kV) are realized with the special plastics used.

The very thin layers of the lamination offer a high transparency of 92-94% on the top side, making the innovative technology perfect for complementing flexible assemblies with LEDs and/or optical sensors.

The photometric properties and light color of the components mounted on the flexible substrate are retained even under the protective coating. Compared to conventional protection methods, the shift in color temperature is only approx. 200 - 300 Kelvins. Since the material composite is highly resistant to UV radiation and at the same time offers high UV transmission, there is no yellowish effect even after prolonged use of the laminated assembly.

Securely Protected, Flexible Modules Withstand a Wide Variety of Environmental Influences

Moisture in the air or directly on an unprotected flexible assembly can impair the functionality of the electronics or even lead to failure. Moisture is considered the main cause of the often insidious corrosion processes, but various chemicals can also promote them. For example, so-called volatile organic compounds (VOCs) can reduce the performance and service life of LED-based lighting systems. Due to dust content and industrial pollution, the air con-

Figure 2: Example of a laminated flexible LED strip in operation.

tains countless particles and a wide variety of (non-visible) substances that endanger electronics in the form of positively or negatively charged ions. They can react with the processed materials, damage them or cause a short circuit. When used outdoors, the electronics are additionally stressed by the changing weather conditions with solar radiation, wind, or water. Furthermore, destructive damage can be caused by unwanted interference (encroachment) by users.

The innovative LumProtect® lamination technology provides reliable protection against a wide range of environmental influences while maintaining the functionality and flexibility of the electronic assembly.

The lamination provides protection against moisture, whereby the production process is aligned regarding the desired degree of protection. A very high level of protection in accordance with class IP67 can be achieved. Tests have shown that the special plastics used in the protective coatings are highly resistant to various chemicals and VOCs, which ensures the service life of the electronics both indoors and outdoors. Furthermore, the electronics are made robust against physical stress and can also largely ward off unauthorised tampering by humans.

Figure 3: Example of a laminated flexible LED strip.

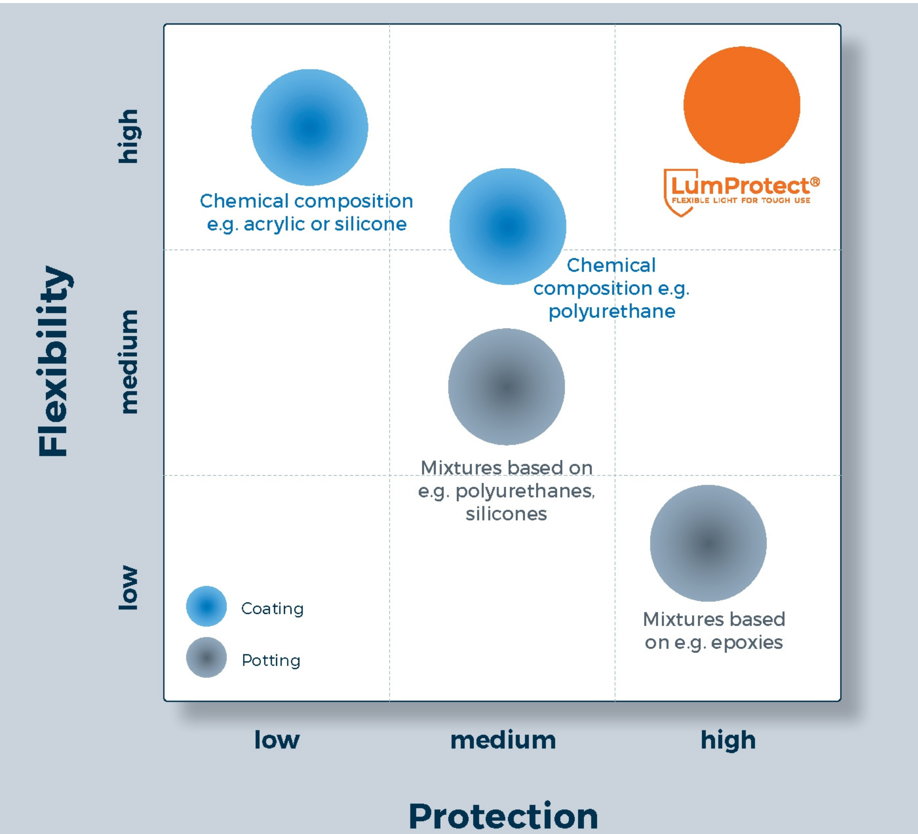


Figure 4: Comparison of coating, potting and laminated protection technologies.

Lamination

The lamination production method protects against humidity (IP67 possible), gases and dust, various chemicals, and physical stress and weather influences.

PROS

- Mechanical flexibility
- Very low material thickness
- High material transparency (92 – 94%)
- Little effect on optical transmission
- Very low weight
- Good chemical resistance
- Good moisture resistance
- High electrical strengths (>80 kV/mm, 4–5 V at 50 µm)
- High shock and vibration resistance
- High resistance to abrasion

CONS

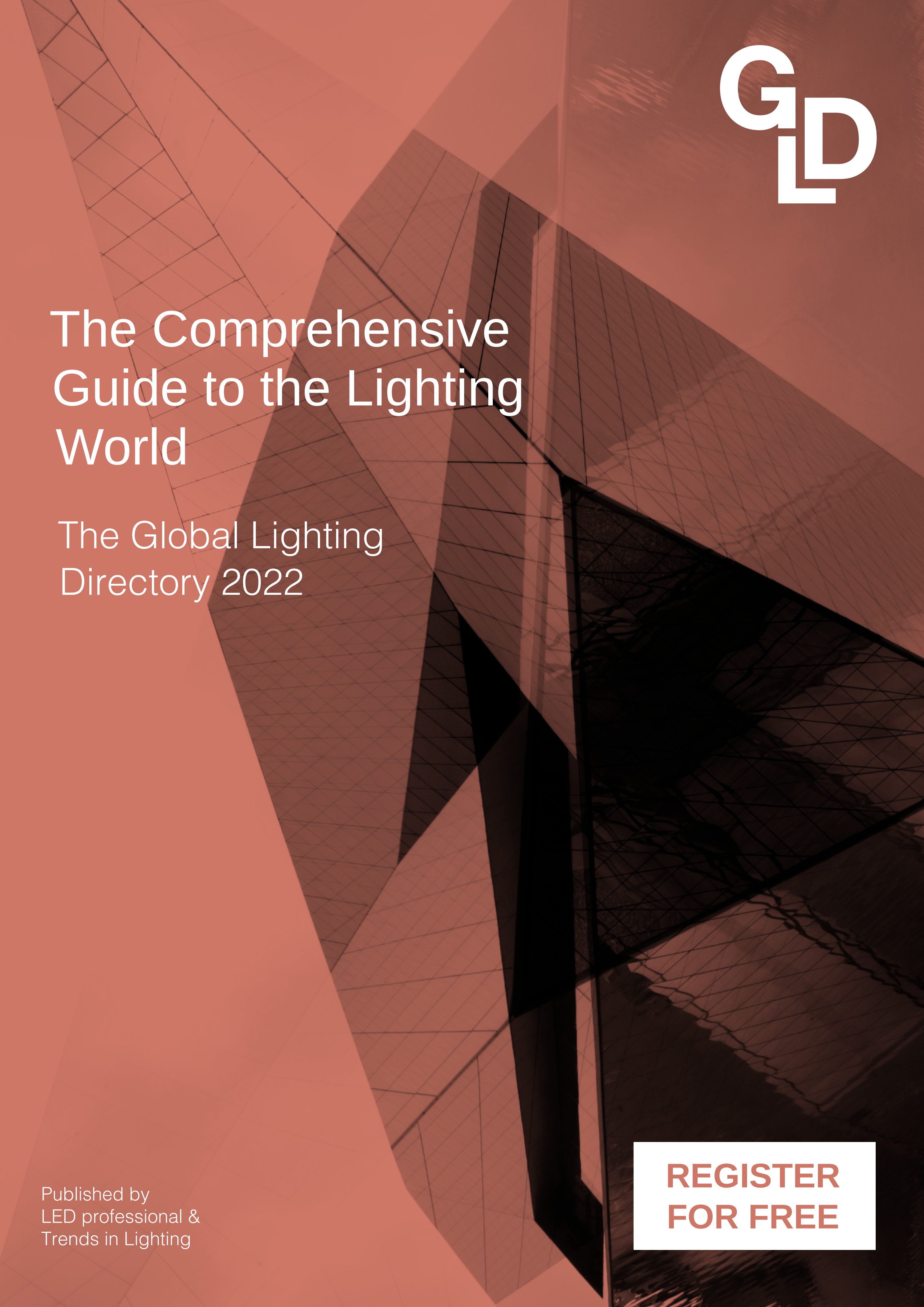
- Limited by the maximum dimensions for components, parts with a height >2 mm are critical
- High process temperature can lead to restrictions in the selection of substrates
- Only for flex, so far, no suitable solution for rigid boards

Technology for Customized Solutions

Lumitronix offers the first laminated LED modules as standard products for common lighting applications, both surface modules and linear strips in different light colors. It is possible to laminate all existing flexible LED modules with LumProtect®.

The lamination technology further offers the possibilities for customization of certain technical parameters. By adapting the layers within the material composite, different designs and colors of lamination can be offered with a kind of textile. The upper layer always remains transparent but can be produced as a structured or smooth surface. Different connection and sealing options with cables, plugs, eyelets & crimp contacts allow easy integration of the laminated assembly into the system.

The current technical parameters of the lamination process are particularly oriented towards the requirements of the lighting industry. Since the production process is carried out 100% at the Lumitronix site, other adaptations for challenging applications can be realized together with customers within the scope of development projects. ■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Living on the Moon with LED Technologies

Daniel HAN, VP Business Development at Beijing Yuji International

The LUNARK habitat mission, designed and constructed by the Danish space architects Sebastian Aristotelis and Karl-Johan Sorensen, aims to simulate the moon's real living environment. The habitat is tested over two months in Northern Greenland, where it behaves mostly like the south pole of the moon, including the extreme temperatures, "the peak of eternal light", the vast white landscape and remoteness. The mission will provide the data analysis for the next human landing on the moon, probably in 2024, according to NASA's current schedule. The last time was Apollo 17, fifty years ago.

Illumination in the habitat doesn't only mean the creation of a lighting environment in the enclosed space, but also living conditions that have to consider the circadian rhythm, emotional feelings and biological responses. There is no-longer any natural light here like that on earth; everything depends on artificial lighting, which provides almost all of the basics of visual and non-visual activities. People don't realize the challenge until they are on site, personally. LED, undoubtedly, is the ideal option for illumination, considering its mature development in both technical and commercialized ways, especially its "digital" features with flexible size and tunability.

Yujileds, the researcher, developer and manufacturer of professional LEDs, participated in the project as the light source partner, with their latest full-spectrum and multichromatic LED prototypes which are designed specifically for this mission and which include the circadian rhythm aspect. Louis Poulsen, founded in 1874, participated as the lighting fixture partner and the tuning sequence developer. This article introduces the basic theories of the circadian rhythm with the LED spectral performance and the engineering of the luminaire with relevant designing principles. With the experiment data, it also indicates how we can utilize LED technologies for such tasks and the results we obtained from this mission.

> *"When we go to the moon, we must thrive, not just survive."*
>
> LUNARK PROJECT STATEMENT [1]

We rarely ask "how will the sunlight change tomorrow?" because, since the birth of human civilization, the sun – a fixed star - shines steadily, every day. People have been used to it for many generations. Objectively, the "Air Mass (AM)", which is the ratio of the mass of atmosphere in the actual observer-sun path to the mass that would exist if the observer were at sea level [2], describes relevant definitions, including the standard solar spectra. The AM 1.5 standard spectrum [3] stretches from the deep ultra-violet to the infrared wavelengths, and the visible light spectrum, which is typically recognized between 380–700 nm [4], only covers it partially. However, the visible light spectrum mostly affects man's circadian rhythm and behaviors and therefore this range is what we are concerned with. The AM 1.5 standard spectrum also indicates an important reference that homogeneous spectral power distribution is ideal for artificial lighting to imitate.

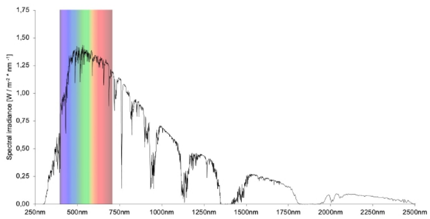


Figure 1: AM 1.5 standard spectrum (direct + circumsolar) in the range of 250-2500nm and 380-700nm.

Man first landed on the moon in 1969 and it is difficult to trace what light sources were assembled in the space capsule. We know it wasn't LED because at that time it was still far away from practical use. Even today, astronauts can only rely on artificial lights for their daily activities and the lighting quality determines if they can accomplish their missions. The LUNARK habitat mission is not only for the short-term tasks but focused on studying how people would thrive on the moon: not just survive. Thus, lighting has to be considered just as it is for all of our full-time activities on Earth. It is difficult to imagine the importance and challenge of lighting quality until we start thinking in this way.

In daily life, we rely on lighting, natural or artificial, for working, studying, entertainment, and relaxing. Light is not just for illuminating something to "see" it, it also provides the correct feelings and emotions for doing things appropriately. Lighting also affects both biological and psychological health.

Figure 2: A 3-month analog mission 1000 km north of the polar circle.

In this case, the illumination principles in different scenes would be quite distinct and should be flexible enough to tune at any time.

Illumination Principles in Different Scenes

Most activities cannot be done without appropriate lighting. The primary scenes in one day can be listed as follows:

Work and Study

Illumination principle: Productive, exciting, concentrative, wakeful, legible.
This scene is the most important part since it is the process of creating productive forces. It therefore requires alertness and concentration; the secretion of melatonin should be suppressed as much as possible to avoid tiredness. In addition, the lighting should be friendly to the eyes with good color rendition and correct chromatics to create a favorable environment for reading, operating, drawing and measuring.

Relaxation and Entertainment

Illumination principle: Low excitement, comfortable environment, legible.
Relaxation occurs during work and study and requires a gradual switch from "exciting" to "peaceful". In this scene the lighting generates more melatonin to help the subjects relax. For entertainment, the scene requires more than white light illumination. The tunable colors are necessary for creating specific environments and here white light is not the key lighting, but rather, dynamic and colorful light play the primary roles.

Pre-sleep

Illumination principle: Sufficient to reduce excitement and promote the secretion of melatonin.
Melatonin will be secreted sufficiently for this scene when the blue light is reduced as much as possible. White light is no longer necessary, instead, the light should be able to create a warm and comfortable environment, aiding sleep without creating any excitement.

Emotional Regulation

Illumination principle: Regulate psychological feelings using different lighting formulas accordingly.
It has been proven that color has the ability to influence a variety of human behaviors such as object recognition, the identification of facial expressions, and the ability to categorize stimuli as positive or negative [5]. When astronauts are kept in a confined space for a long period of time, it is necessary to care for and regulate their emotional and psychological health accordingly.

Lighting Technology

LEDs are unprecedentedly flexible in both spectral engineering and product modality. The Yujileds portfolio offers a broad range of available spectral options for both semiconductor and phosphor-converted LEDs – covering almost all of the visual wavelength with different FWHMs (Full Width at Half Maxima), by matching with each other. It is possible to design the spectrum using full turning. Furthermore, thanks to the illumination theory, LEDs can be made in compact sizes and can be driven individually with relevant programs. This is significant for limited space, especially for a habitat where every inch is expensive.

Natural light spectrum LEDs for key lighting

White light is the primary composition for all lighting scenarios and therefore plays a vital role in mimicking natural light in an enclosed habitat. The selection of LED sources is based on homogeneous spectral power distribution and should cover as broad a visual wavelength as possible without missing obvious energy or creating spiculate peaks to avoid distortion compared to sunlight.

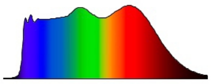
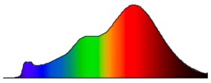
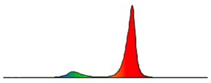
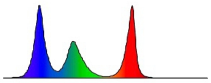
Scene	Spectrum	CCT	M/P ratio	CRI	Visual color
Work and study		5000K	0.933	95	
Relax and entertainment		2700K	0.522	98	
Pre-asleep		-	0.263	-	
Emotional regulation		-	-	-	

Figure 3: Spectrial recipes for the different lighting scenes based on Yuji LED components.

Figure 4: Lighting fixture designs with LED strips.

Meanwhile, two different color temperature LEDs should be selected to formulate stable and consecutive spectra during tuning. Therefore typical warm white of 2700 K and daylight white of 6500 K are chosen to be the white light bases.

Monochromatic LED for specific hues and spectral integration

Generally the monochromatic LED does not work individually but always cooperates to be added to the white light LEDs to create different scenes. The monochromatic LED achieves saturated blue, green and red that cover most of the CIE 1931 diagram, which stands for a human's visual range. Therefore, with the combination of full-spectrum white light and monochromatic LEDs, these LED light sources are capable of representing most of the colors and white lights.

Bactericidal effect from the UVA wavelength

Environmental cleanliness is extremely important especially with the global impact of Covid-19. The sterilizing device becomes necessary and the ambient lighting can help with this. The full-spectrum LED contains 400–420 nm wavelength radiance which has been proven to be effective in killing viruses. Germicidal properties of violet-blue visible light (380–500 nm), especially within the range of 405–450 nm have been shown as an alternative to UVC irradiation in human occupied whole-room disinfection scenarios where it has shown reduction of bacteria and surgical site infections. 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. , and in fungal species such as Saccharomyces spp. and Candida spp. 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) [6].

Lighting Fixture

The panels used in the LUNARK mission are made in three different sizes and two large panels, 10 mm by 1250 mm over the working desks. At the top of the hab, there is a triangle-shaped panel in each of the pods.

The construction of the panels is the same for the rectangular and triangular panels. The LEDs are made on flexible strips then on a 3 mm aluminum backplate. This serves the purpose of being a heat sink that can dissipate the heat of a large number of LEDs.

The 40x40 aluminum V-slots are mounted on the sides of the backplate. These are ideal for fastening the backplate and the plexiglass dissipator. The plexiglass used is 3 mm thick, 3570 kg/m^2, blank white with color code WH14, and has a 47% light transmission (**Figure 4**).

LED strip

Inside the rectangular panel, the amount of space for the LEDs is 15.4m. Since the V-slots were 40 mm wide, they blocked 80 mm of the total length of the backplate and due to the LED strips coming in 10cm cuts, the engineers have to have a length divisible by 10 - thus it ended up with 110cm strips in 7 rows, but both the RGB and WW (2700K) / CW (6500K) strips give a total length of 110*7*2 = 1540 cm.

Controller

The LED strips are controlled by a microcontroller; more specifically an ESP32. The ESP32 is a WiFi-enabled MCU, meaning the panel can be placed anywhere and it could wirelessly receive data from the main computer in LUNARK, aptly named ODIN. The ESP32 runs on 3.3 V to –5 V and therefore cannot directly control the LEDs running on 24 V. For this reason the engineers use IRF520 MOSFETs between the ESP32 and the LED strip, enabling a quick on / off switch, emulating PWM and thus the intensity of the light.

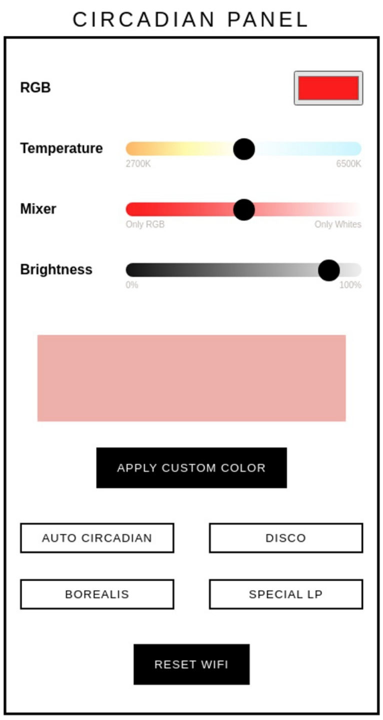
ODIN creates a WiFi hotspot to which all of the “Ravens” (ESP32’s) can connect to. ODIN hosts an MQTT server, which is exposed to all connected devices. MQTT is a lightweight data transfer protocol, often used in IoT devices.

The MCU requests the current time and date from the main computer and uses this to decide which type of circadian sequence it should play. These circadian sequences are hardcoded, developed by Louis Poulsen.

Future Panels

If the panels are to be standalone, we need a different interface, since we cannot sell an ODIN with the panel. Therefore the engineers create a web UI (**Figure 5**) that can be accessed if connecting the ESP32 to the WiFi.

The ESP32 wakes up and checks if it has a remembered WiFi connection. If it does, it tries to connect. If there is no remembered WiFi or it cannot connect to it, it opens up the configuration portal. This creates a WiFi hotspot. It navigates to 192.168.4.1 and in there it inserts the WiFi SSID (name) and password. The ESP32 reboots and connects to the now remembered WiFi. Shown below is the connection to the same WiFi and navigating to the address, UI. Users can create a custom color by tuning RGB and CW / WW or using the built-in features. The “Auto Circadian” feature will start playing a defined sequence, using the current time of day.



SAGA
Space Architects

Figure 5: The web UI for circadian wiring diagram of circadian “Raven”.

Observations and Study

To observe and analyze the team members’ behavior and health during the mission, psychologists and scientists, Anders Kjærgaard, Gloria R. Leon and Konstantin Chterev measured their living and working status over the 60-day stay in the lunar analog habitat. The study indicated the circadian lighting system was a highly important component of the habitat; self-reports by teammates indicated that the lighting system facilitated regular sleep-/wake schedules, cognitive activation, comfort, and time orientation. The configuration of the workspace regarding the

Item	TM 1 (%)	TM 2 (%)
Problems with gear and equipment	12.5	62.5
Feeling of camaraderie/closeness with teammate	87.5	100
Concern about the well-being of my teammate	37.5	38
Enjoyment of the Arctic environment	87.5	87.5
Concern about how effectively my teammate and I are working together	25.0	62.5
Feeling down/low or stressed because my teammate is feeling that way	12.5	12.5
Tension or argument with my teammate	25.0	37.5
Satisfaction in making good progress today	100	100
Satisfaction that equipment is working properly	87.5	87.5
Satisfaction that I am able to cope with the challenges	87.5	87.5
Concerns about the effectiveness or safety of decisions I made today	0	0
Fear of being injured	37.5	25.0
Worried about family, friends	25.0	25.0
Worried about encountering bad weather	25.0	37.5
Loneliness, homesickness	0	62.5
Lack of privacy, time for myself	25.0	62.5
Personal Hygiene (wanting to be cleaner)	12.5	0
Muscle or joint ache	25.0	12.5
Headache	25.0	0
Other physical problems	12.5	0

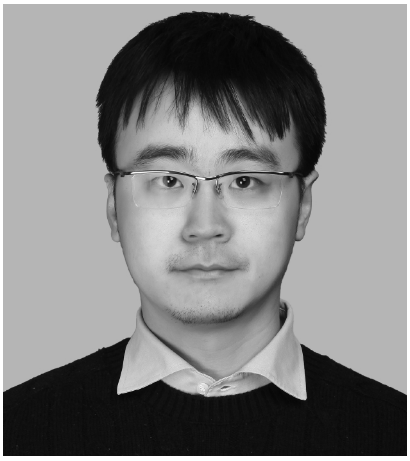
Table 1: Results of the survey for two team members (TM 1, TM 2). Mean percentage creating periods in which a particilar item was endorsed.

placement of individual desks, the ability to flip them up against the wall, multifunctional and collapsible furniture, storage space to avoid clutter, and the occasional use of the airlock for work and privacy facilitated task performance and mitigated interpersonal conflicts. Both team members' use of isolated areas of the habitat for privacy facilitated the diffusion of tension and thus served as a means of coping with stress. The interior materials, color scheme, and the designed comfort of the sleep pods promoted relaxation and made the habitat feel more like an Earth home. The comfortable sleep pods also facilitated individual privacy as needed [7].

Lighting in the habitat contributes important effectiveness, but of course not the only one. The study concluded that a highly important comfort and sleep feature was the installation of a circadian light system with daily variation, high color rendering, and simulated sunsets and sunrises. According to TM #2's (Team member #2) self-report, these features promoted a healthy sleep-wake cycle, a sense of time, something to look at, and made the habitat feel natural: "It felt like we had large amounts of diffused sunlight flooding into the habitat, which in ways hard to define made it really pleasant to be there. The mornings especially were nice." TM #1 (Team member #1) stated that another comforting aspect was "the contrast between the interior and the exterior of the habitat. From the outside, the habitat shell is black with jagged edges and almost looks intimidating; the inside is the exact opposite - light colors, soft materials, and rounded edges."

Summary

With the rapid development of LED technology and the understanding of the biological effectiveness from lighting, it is not difficult to find the illumination principle of LED is more and more suitable for achieving different and specific lighting purposes, and it is also not difficult to believe the LED technology mentioned in this article is feasible to be applied in a real space capsule. The latest LED development does not only offer a lighting environment but provides conditions for thriving rather than just surviving. We are confident that LEDs could illuminate the future. ■



Author: Daniel HAN
With a technical background in photoelectricity, Daniel is currently the VP of business development at Yujileds. He is focused on creating, administering, and making strategic decisions on market research, R&D of innovative LED technologies and products, as well as global business strategies implementation. With profound understanding of the LED technology and extensive experience in different LED industries, Daniel leads sales, R&D and marketing teams to achieve the goals of the group company, and concentrates on utilizing and optimizing his expertise and resources to provide comprehensive solutions for various applications and markets.

About Yujileds Yujileds started to make LED phosphor materials in 2006 when white LEDs were still in a very early stage. Today, Yujileds is well known for our research and full line-up production of LED phosphor from ultra-violet to near-infrared, and they are proud to commit to providing superior stable and efficient phosphors to the worldwide markets. The industrial structure of both phosphor and LED give them a unique view to develop our spectrum recipes. Compared to the general LED manufacturers, Yujileds has comprehensive information in evaluating the feasibility for both technical and commercial aspects. LED spectrum technology is not only about the quality of white LEDs, but also for different applications which have specialized requirements in lighting.

Yuji is one of the few companies that provide the service of designing or customizing a specific spectrum for clients, their confidence comes from the years of accumulation in focusing on the spectrum technologies and the control of LED phosphor and LED die supply-chain with thousands of successful cases in the past years. Innovating LED technologies and giving them commercial values are our eternal driving force.

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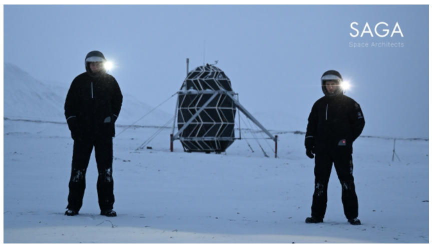

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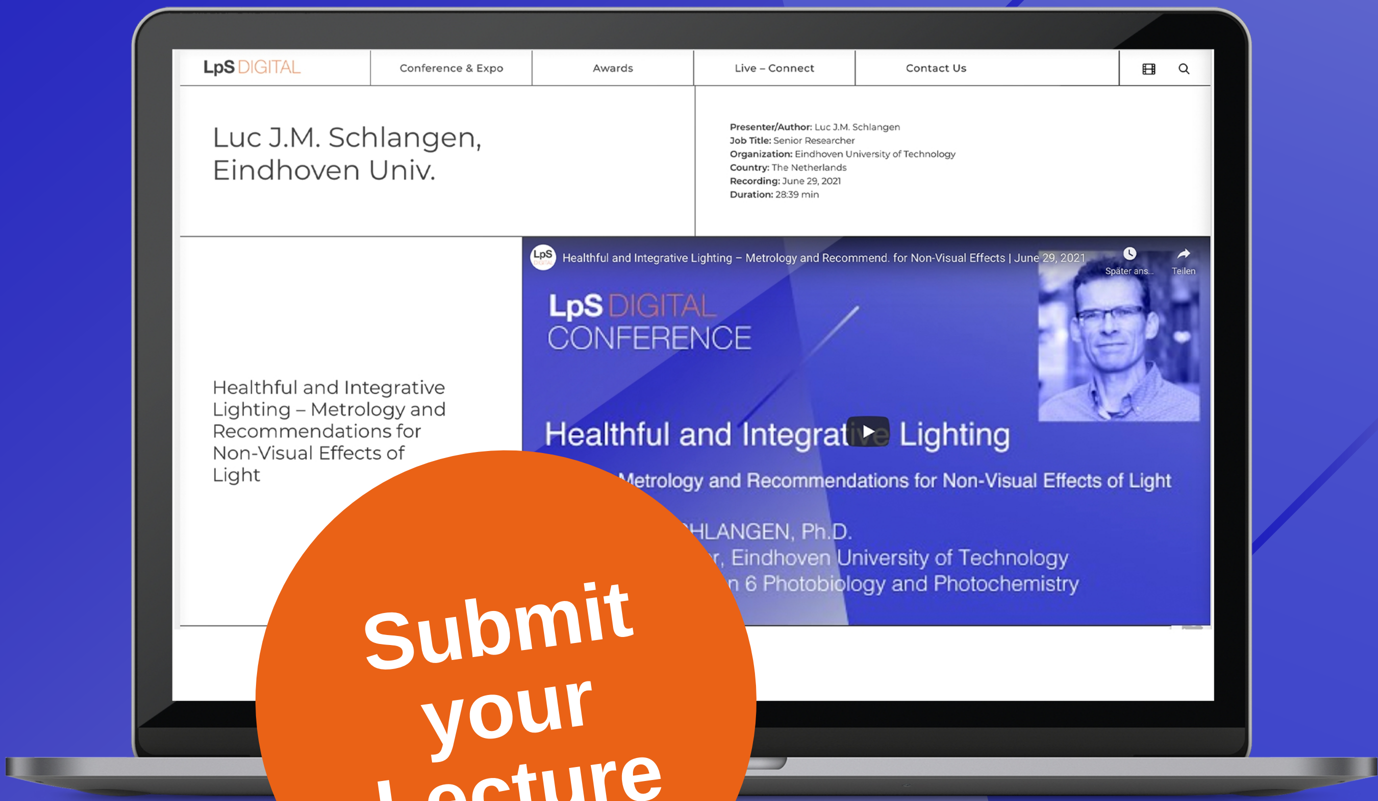

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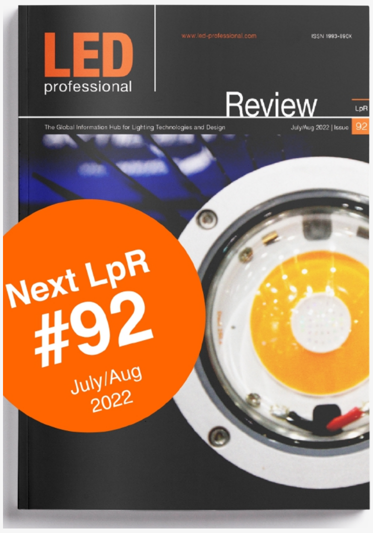

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Imprint

LED professional Review (LpR)
ISSN 1993-890X

Publishing Company
Luger Research e.U. | © 2001–2022
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