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LED professional Review

LpR

The Global Information Hub for Lighting Technologies
July/Aug 2020 | Issue 80

NEW! Now available with Advance CertaDrive X Drivers. The ideal choice for economical indoor commercial lighting.

CERTAMATCH SOLUTIONS
for Troffer and High Bay Fixtures

The Market Trend

Average unit prices of high-running indoor LED fixtures are plummeting.

OEMs are resorting to importing and reselling finished fixtures or using lower cost components with minimal warranty or technical support in order to remain competitive.

There is Another Way...

What if you could have **high quality** components at a **competitive price**?

What if you could have onshore sourcing for **shorter lead times**?

What if your components had a **5 year limited warranty** that is serviced by your components supplier?

CertaMatch:

A Perfectly Paired Module + Driver System

- Designed for common lumen outputs
- Standard and premium LPW for external certifications
- Out of the box ready, no programming needed
- Ideal for Stock and Flow Luminaries
- Made in North America for reduced lead times
- Fast Approbations
  - Fortimo QuickCheck program
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ADVANCE
by Signify

Environment-related Lighting

The global developments caused by the Corona pandemic have shown us that sustainability and environmental protection must become central issues in our societies. Areas can no longer be viewed in isolation and the global interrelationships of our economic activities must be taken into account responsibly.

The lighting sector is no exception and can contribute in many ways to improve living conditions and support the circular economy with sustainable product concepts. One way is through disinfection and sterilization, a field where a great deal of research and development is being carried out in order to validate the findings.

In this issure of LpR we have focused on sustainability by covering topics like UV LEDs, sterilization and disinfection, reactive oxygen species, eco design and labelling and ciruclar economy. On the other hand, we also wanted to give you an understanding of the topic of sustainability in a braoder sense, and so have included articles on human centric lighting, tunable lighting and horticultural lighting. As a special feature we have also dedicated a section to Lidar technology.

We are also interested in building a bridge to the applications themselves and will continue to publish more articles on lighting design in the future – this time featuring the topic of media data.

We hope you enjoy reading our carefully selected articles. Feedback from you is always appreciated.

Yours Sincerely,

Siegfried Luger

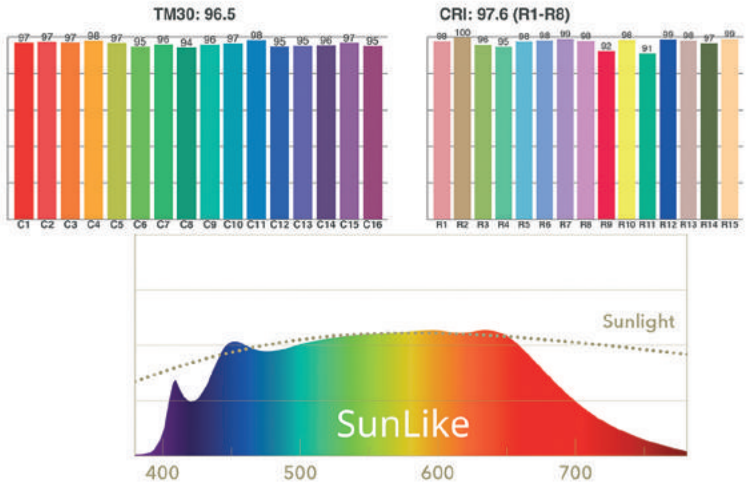
Luger Research e.U., Founder & CEO
LED professional, Trends in Lighting, LpS Digital & Global Lighting Directory
Photonics21, Member of the Board of Stakeholders
International Solid-State Lighting Alliance (ISA), Member of the Board of Advisors

ADVERTISING INDEX

WE BRING YOU THE SUN_{LIKE}

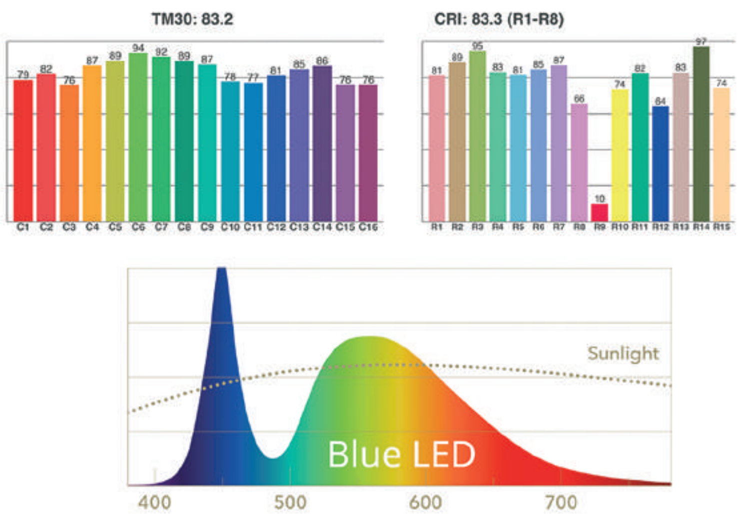
The only TRUE solution for Circadian Lighting

No UV
No Blue Peak - M-EDI like D65
Best Colors at any CCT
Following the Sun spectrum



Traditional LED
Blue chip

Big Blue Peak
Very Low M-EDI (490nm)
Low color rendering
No natural spectrum



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SunLike
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Donatas STOČKŪNAS

Donatas Stočkūnas has been involved in the lighting industry for almost 10 years. For the last 7 years, Donatas as the Commerce Manager at AKTO leads customer support and marketing teams. He is also in charge of controlling the full scope of sales processes, expansion to the new markets and implementation of other company goals. Interest in the LED lighting products manufacturing processes – components supply, quality control, customer needs and other industry news helps to seek the whole company's objective of providing the highest quality components for luminaries manufacturers, shopfitting companies and other interested parties.

The Basic Sales Arguments for LED Lighting

From the very beginning of light emitting diodes (LEDs), mass production has passed the half century mark. In the past fifty years, the LED lighting industry has developed exponentially and continues to grow. Over this period of time is has become widely known that LED lighting is superior in both energy and costs savings, environmental aspects and has a more versatile range of functionalities. Despite these facts, there is still a considerable amount of incandescent, fluorescent lights (CFL) being used. If your home, office or other commercial property is illuminated with insufficient lighting solutions, here are the main points to consider if you want to know why the transition to LED lighting can be beneficial for you.

One of the main advantages are the economic factors. For starters, LEDs not only have a life span of up to 50,000 hours, but they also reduce electricity costs by consuming less power while receiving the same light (lumen) output. In comparison, conventional incandescent bulbs and fluorescent lights consume more energy and only last approximately 1,200 to 8,000 hours. So in the long run, LED lighting reduces both electricity and maintenance costs, which can quickly add up – especially when it comes to commercial applications.

LED lighting is also known to be eco-friendlier. Products from leading LED lighting manufacturers not only meet energy efficiency standards and environmental requirements but usually even exceed them. In most cases, the composition of LED lighting products contains only those materials that can be recycled. Moreover, LED lights are free from toxic chemicals like mercury or harmful gases that can be found in fluorescent lights.

In addition to the advantages discussed, LED lighting solutions offer wider areas of application as well as more functionalities. For instance, increasingly popular tunable white LED modules allow you to freely change the color temperature from 2700 K to 6500 K just with one product! The reasons that this is beneficial range from aesthetic to therapeutic.

To begin with, it is well known that cooler light, such as daylight, has a positive effect on our productivity. This feature is important, not only in schools or offices, but in our homes, as well. This is especially true for those that work remotely. Imagine how useful tunable lighting could be if you had a work station in your bedroom or living room. During work hours you can adapt it to cooler light and later, when it's time to rest, you can create a more comfortable and relaxing atmosphere by changing the color temperature to warm light. Matching the light color according to natural day and night rhythms is also beneficial to our biological clocks. In the long run it can help with your sleep schedule at night and concentration during the day. It is even believed that cooler light can create a psychological effect, making you feel a little cooler on a hot and sunny day and warm light making you feel warmer on a cold, rainy day. This feature can be beneficial to various businesses where it is aimed at creating the best possible customer experience. Tunable white LED products can also be very beneficial in museums and art galleries because you can easily change the lighting depending on the particular exposition. Beyond that, LEDs don't emit UV light unless they are specifically designed to do so. Furthermore, the spectrum of LEDs can be adapted and tuned to avoid emissions that could harm and destroy artwork.

Besides all that, tunable white LED luminaries or RGB LED products enable you to reproduce millions of colors and have a variety of color temperatures without the use of additional light filters that would be required when using conventional lights. More than that, LED lighting systems can be controlled with the help of digital controls, ensuring maximum efficiency and comfort. ■

D.S.

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Making LED Lighting Solutions Simple™

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APPOINTMENTS

Laura Voss Joins Foundry London

Laura Voss joined Foundry, based in London, as a Lighting Designer. Over the past five years, Laura has worked in the lighting design industry at Nulty, dpa and Isometrix. During her time at Isometrix, Laura worked on many high profile projects spanning the UK like Annabel's London and Antony Gomley's 2019 exhibition at the Royal Academy of the Arts, as well as further afield. Laura's experience to


Laura Voss

date has seen her work across a range of sectors including commercial, hospitality, residential, leisure and urban space.

Before beginning her career, Laura completed her degree in Architecture and her MA in Architectural Lighting Design. Her Master Thesis explored the various issues resulting from light pollution, and examined different strategies and approaches, to control and reduce these problems.

Laura is passionate about the lighting industry, and her work within, and regularly attends industry conferences, exhibitions and events to further her knowledge, and to keep updated on the latest market trends and technologies.

Laura is currently working on several large International projects in the retail and hospitality sectors as part of her design work at Foundry London. ■

New WE-EF Group Managing Director

WE-EF announced that Stephan Fritzsche is to step down at the end of September and Mario Dreismann is the incoming Group MD. The purpose of the early announcement is to ensure continuity and promote development. After setting the course for the future of WE-EF by joining the Fagerhult Group three years ago, Managing Director Stephan Fritzsche has decided to initiate the succession process after 34 years in the family business and to step down as of 30 September this year.

Mario Dreismann, who holds a degree in Business Management, joined WE-EF on 1 June and is working together with Stephan Fritzsche until 30 September during the handover period. On 1 October 2020 Mario Dreismann will then officially take over full responsibility from Stephan Fritzsche as Managing Director of the WE-EF Group.

After graduating with a Degree in Engineering, in 1986 Stephan Fritzsche joined the family business founded by his father Wolfgang Fritzsche in Bispingen in 1950. He successfully led WE-EF through major challenges such as globalisation, digitalisation and the LED revolution to its current strong market position, and consistently promoted the development of a robust, flexible and innovative company structure. His management style, which is characterised by responsibility, integrity and fairness, has left its mark on WE-EF and has earned him the recognition and respect of employees, business partners and industry colleagues alike.

The aim of the succession plan is to hand over responsibility to the new management of the Fagerhult Group as smoothly as possible. "We are pleased to welcome Mario Dreismann as the future Managing Director of the WE-EF Group. He is well-qualified to carry forward the success, the specific character and the innovative spirit of WE-EF in an increasingly complex world," Stephan Fritzsche said in commenting on his chosen successor.


Stephan Fritzsche (left) and Mario Dreismann (right)

Mario Dreismann has international management experience as a business leader and is an expert in the construction and lighting industries. Following his graduation in business management, Mario Dreismann was head of sales and marketing at Dorma for several years. In his most recent position as CEO at Ansorg and a member of the management board of the Vitra Group where he was responsible for the shopfitting division. "I am passionate about good architecture and lighting, two things that WE-EF combines in an ideal way. At the same time, I see myself as a team player with a strong interest in products, leadership and people," Mario Dreismann explained. ■

Filix Lighting Appoints New MD For Asia-Pacific

Filix Lighting with its European HQ in Croatia specialises in conceptual light design and engineering. Earlier this month the announced the appointment of **Alan Dowen** as Managing Director for their APAC regional presence, covering The Philippines, Indonesia, Malaysia and Vietnam from a new Filix Lighting office based in Manila, Philippines.


Alan Dowen

With an increasing end client and channel base across the region, Filix Lighting with their renowned CEO Marko Jurman and his team, see Alan with his team management skills, regional knowledge and location base as an ideal leader to grow their presence, while supporting those key end clients and lighting partners that they hold dear.

Alan has been in management for 20+ years working in and leading sales, engineering and teams in constant results within key roles. Also specialising in new business sales and operational set up, Alan has worked in regions from Manila, Singapore, Kuala Lumpur, Jakarta and Hong Kong on new build projects for other manufacturing units during the last 15 years.

"This is an exciting opportunity to expand in experience and within an industry leading lighting manufacturer who has a wealth of experience and knowledge. Being based in my home territory, within an exciting region as it now leaves a 'dark period in time' following C-19, will give me the challenges and rewards many search for. I'm looking forward to working with leading industry expertise, leaders and clients who have the same dreams of achieving excellence as I do". ■

Zumtobel Announce New Supervisory Chair

In May Zumtobel Group formally announced the appointment of **Karin Zumtobel -Chammah** as the new Chair of the Supervisory Board. After finishing her MBA at the University of Fribourg, she held leading management positions at major financial institutions. In 1996 Ms Zumtobel-Chammah joined the Zumtobel Group where she held a number of marketing positions and most recently headed the Arts & Culture Department before joining the Supervisory Board in July 2019.


Karin Zumtobel-Chammah

The Zumtobel Group is an Austrian company specialising in lighting technology headquartered in Dornbirn, Austria. Zumtobel engages in the development, production and sales of lighting technology and offers lighting solutions, luminaires, lighting management and lighting components for indoor and outdoor applications. ■

New Light + Building Director

Maria Hasselman hands over to **Johannes Möller** from July 2020. Möller is an experienced graduate trade-fair, congress and event manager, gathering sales experience with the Prolight + Sound trade fair for many years before spending four years as personal assistant to the President and Chief Executive Officer of Messe Frankfurt. Subsequently, in 2017, he was appointed Director of the Brand Management and Development Team in the company's Technology Business Unit.

Johannes Möller is clear about the challenges facing the lighting and building-services sector. "My aim is to add to the experience of the fair for all concerned, including through the use of digital channels. Accordingly, the portfolio will soon be supplemented by a variety of formats, such as podcasts, online product and trend shows, as well as internet discussion forums", says Möller. "At the same time, there can be no doubt that personal encounters are irreplaceable. This applies not only to confidence-building measures and product quality analysis but also, of course, to networking and the exchange of ideas and information. I am looking forward to achieving this aim by continuing the close working relationship with our cooperation partners, the ZVEI and ZVEH associations", adds Möller.

With the handover of responsibility, Light + Building is also embarking on the next decade with a new managerial generation. Johannes Möller has been working together with Maria Hasselman since the beginning of the year, which gave her the opportunity to pass on the benefits of her extensive knowledge and experience, thus guaranteeing a smooth changeover in the interests of Light + Building and the worldwide brand family. Johannes Möller will report to Iris Jeglitza-Moshage, Senior Vice President of Messe Frankfurt.

Maria Hasselman will retire from Messe Frankfurt in August 2020. "Maria Hasselman has an unrivalled ability to immerse herself in highly complex subjects and was thus able to manage perfectly the trade-fair structures and marketing of Light + Building. Moreover, we profited from her ability to interconnect the different disciplines of this extremely varied sector and to understand the individual challenges facing them", says Iris Jeglitza-Moshage honouring Maria Hasselman's twenty years with the company. "I would like to have seen this year's anniversary edition of Light + Building as the crowning glory of Maria Hasselman's work. Unfortunately, the coronavirus put paid to this wish. We will miss her. At the same time, we wish her all the very best for the future."


Johannes Möller

After working in sales for three years, Maria Hasselman assumed responsibility for Light + Building and its approx. 1,900 exhibitors from 80 countries in 2003. At that time, the trade fair attracted over 110,000 visitors to Frankfurt am Main – impressive figures that appear almost modest fifteen years later: in 2018, some 220,000 visitors from 150 countries came to Frankfurt am Main to see the products and services being presented by no less than 2,700 exhibitors.

"There was nothing automatic about the way Light + Building developed", says Maria Hasselman. "One of the keys to success was interdisciplinary thinking and planning. It was no less necessary to establish links between the trade, artisans, the industry, planners and architects than between the various disciplines in the field of building-services technology. At the same time, this success would not have been possible without the commitment of our partners and the media", adds Maria Hasselman.

Light + Building with Intersec Building will be held in Frankfurt am Main from 13 to 18 March 2022. ■

Roger Sexton Joins Stoane Lighting

Dave Hollingsbee MD at Stoane Lighting says "We are delighted to announce the appointment of **Roger Sexton**. He joins our Senior Leadership Team to boost Business Development and support Key Specifiers. Roger arrives off the back of 20 years at Phillips Lighting, followed by 12 years at Xicato Inc. Having been there since its inception he has helped in establishing them as world leaders in high quality light engines.


Roger Sexton

Aside from these core roles, supporting lighting designers and engineers internationally, Roger is a Fellow of the Society of Light and Lighting and sits on one of their committees, a member of ICOM, interfaces with several universities and participates in industry-wide research. This depth and breadth of knowledge across numerous areas of the industry would be eagerly welcomed by any right minded lighting company, so we were as surprised as we were delighted that he agreed to join ours. Add to this his down-to-earth style and frank honesty, we think will be a great fit and a fantastic asset.

"The fun begins today." – Roger

Mike Stoane Lighting is an employee owned specialist manufacturer of architectural lighting equipment. The company was founded by Mike in 1995, when he started making lights on a lathe in his lock-up in Edinburgh. "We have outgrown the lock-up now, but our lights are still made by us, in Scotland. This ensures excellent quality and flexibility and is something we are very proud of. We design, manufacture and assemble all of our products in the UK, at our premises just outside of Edinburgh. We have a very well equipped workshop and a talented team made up primarily of product designers, engineers, assembly and technical staff." ■

Marianne Simensen Joins Rebel Light

Marianne Simensen has recently joined the Rebel Light team to support the Norwegian design community as part of a growing Nordic sales team. Simensen started out as an electrician before moving into lighting, and subsequently enjoyed 6 years at Fagerhult and 12 years at Louis Poulsen.

"Marianne brings a whole lot to the table as she joins Rebel Light, a lighting company looking forward to celebrating its 10th anniversary. This level of experience and knowledge makes a great addition to our passionate team. On top of that we have a new punk rock colleague with a fantastic business attitude and a true passion for design & architecture." ■

Inventronics Appoints New General Manager Of Europe

Inventronics, a global leader of the LED driver market, is pleased to announce that **Jeroen Van Velzen** has been appointed General Manager of Europe and will be leading the company's European strategy and execution. Inventronics new innovations and increasing demand from its customers has led it to look for an addition to the European team who will provide exceptional service and management.

"Jeroen has an impressive track record of leadership and strategy development in our industry," says Marshall Miles, CEO of Inventronics. "We are continuing our investment in the European market and Jeroen is another key person as we look to build a high-performance team, strong customer relationships and world-class service to the lighting OEMs across Europe."


Jeroen Van Velzen

Van Velzen is an accomplished leader with significant experience in the lighting and technology industry. He has served in several key leadership positions at widely known companies such as Rena Electronica BV, Lemnis Lighting, Philips and Aruna Lighting which he founded in 2016. Van Velzen has led several global commercial and consumer sales teams where he continuously brought sales growth, has overseen many business units, manufacturing lines, internationalization of companies and redefining company strategy, deployment and implementation.

"I am excited for this opportunity," says Van Velzen. "Inventronics has industry-leading products and best-in-class service. I am committed to enriching their strategic sales plans and helping grow the European channel. I look forward to collaborating with our partners to show them how Inventronics can provide the solutions and tools they need to build their business."

Van Velzen's strong leadership skills and proven successes have already made him a key addition to the Inventronics team. He will complement and enhance Inventronics' ability to meet the needs of its customers as it continues to provide quality, innovative products to the marketplace. ■

Douglas Leonard Begins IALD Presidency

Douglas Leonard assumes the 2020/21 presidency of the International Association of Lighting Designers. The IALD has been supporting its members for 50 years.


Douglas Leonard

Douglas Leonard statement in full: "I am excited and hopeful for the growth and challenges we face as a profession as we move into our next 50 years.The scope of lighting design work has continued to expand and the complexity of that work has increased. Lighting designers have multiple responsibilities they did not have 50 years ago and must manage across a variety of platforms and engage large and changing groups of stakeholders. There are evolving restrictions relative to codes and regulations. Accountability has increased. Clients are expecting services beyond lighting design, which can impact how services are delivered and how a business is structured. As in other professional fields, there is more work—but it is more complex and requires more technical knowledge and soft skills. The work of the IALD keeps us at the forefront of these changes while continuing to excel at serving our members." ■

HUMAN CENTRIC LIGHTING

Bridgelux – New Vesta Product Line Versions

Bridgelux announced commercial availability of new versions of its Vesta product line, adding full natural spectrum white point options to the industry's largest portfolio of tunable white solutions. Vesta Thrive, the winner of a 2020 LightFair Innovation Award, leverages patented Thrive technology to deliver the closest spectral match to natural light available in an easy to use tunable white solution. As

Vesta Thrive

part of the transition to human centric lighting, there is increasing demand for "natural" light sources. The evolution of the human species has conditioned us to thrive in daylight hours by the light of the sun, and after dusk, in the warm glow of fire. Vesta Thrive enables the development of luminaires that not only deliver natural full spectrum lighting, but also allow new opportunities to personalize lighting, tailoring our environment to individual preferences or task-oriented needs.

As announced last month, Bridgelux has developed a new metric to quantify the naturalness of light. Average Spectral Difference (ASD) averages the differences of the spectral peaks and valleys between a light source and a standardized natural light source of the same CCT. With extremely high CRI and TM-30 metrics and extremely low ASD values, Vesta Thrive is the closest match to natural light available in the market.

Bridgelux is continuing to expand its portfolio of human centric lighting solutions with additional Thrive COB and linear modules including V SeriesTM V8, V Series HD V4 and V6, and EB SeriesTM linear modules. Samples of these Thrive products are available now.

"Despite the global pandemic challenges, this remains an interesting and exciting time for lighting innovation," said Tim Lester, CEO of Bridgelux. "Bridgelux is a committed technology partner, ready to help our customers navigate the transition to human centric lighting. The combination of our Thrive and Vesta Series products constitutes a unique solution tailored for natural, human centric lighting. A total solution, also incorporating our Vesta Flex driver and controls products, enables rapid integration of this exciting new technology, accelerating the development of differentiated market leading products." ■

NatureConnect – An Innovative Lighting System Inspired by Nature

Signify, the world leader in lighting, introduces NatureConnect, a lighting innovation inspired by nature to make people feel happier and healthier. The system is built on proven biophilic design principles, which use elements of nature in interior spaces to create healthy, engaging and inspiring environments. The first implementation of NatureConnect is currently taking place at one of Skanska's offices in Warsaw, Poland, a leading international project development and construction company.

In our modern world, people spend on average more than 90% of their time indoors, where they lack access to proper daylight to support their wellbeing. Exposure to the right amount of light during the day, as well as the colors and dynamics from nature, are vital to us in many ways. They strongly impact our mood, energy level, comfort, quality of sleep and our health and wellbeing in general. The importance of healthy and engaged employees has become a boardroom priority. NatureConnect's lighting proposition is designed to benefit the body and mind, and in return, lead to increased productivity, engagement and workplace satisfaction.

NatureConnect is built on proven biophilic design principles, which use elements of nature in interior spaces to create healthy, engaging and inspiring environments

Office workers spend the majority of their time indoors. The quality of the space influences their health, comfort and efficiency. At Skanska we have been aware of this fact for many years. That is why the innovative and environmental-friendly solutions in our buildings support people's wellbeing. One of these solutions brings natural daylight indoors. Research shows that quality lighting significantly impacts how we feel and how effective we are. "The project which we conduct with Signify provides us a new opportunity to continuously improve people's office experience, which makes us very excited about our collaboration going forward", said Katarzyna Zawodna-Bijoch; President and CEO at Skanska's commercial development business in Central Eastern Europe.

NatureConnect combines various LED luminaires – Daylight, Skylight and Lightscape – with intuitive control to create lighting scenes tailored to people's needs, based on proven and valued natural experiences:

- Supporting our natural rhythm: Mimicking the rhythm of sunlight to support us to be active during the day and sleep well at night.
- Providing a view to the sky: Creating the perception of space beyond the walls to give a feeling of freedom and sense of time.
- Being immersed in nature: Bringing the colors and dynamics from nature to stimulate positive emotions, boost creativity and support people to actively work together.

We have become the indoor generation, living in an 'always-on' world, with a work-life balance more demanding than ever before. Many companies are shifting their approach and realize that investing in employee health and wellbeing is paying off. After all, flourishing employees means a thriving business", said Olivia Qiu; Chief Innovation Officer at Signify. ■

SOLID STATE LIGHTING

Lumileds Maximizes Field Usable Lumens: New LUXEON HL2X LED

Lumileds introduces the LUXEON HL2X, the ideal choice for roadway lighting and sports lighting fixtures with the highest flux and efficiency in an industry standard package.

"With 318+ lumens at 700 mA and 85 °C, LUXEON HL2X delivers more 'field usable lumens' for optical engineers to work with."

ALVIN YEOH, SENIOR PRODUCT MARKETING MANAGER AT LUMILEDS

"With 318+ lumens at 700 mA and 85 °C, LUXEON HL2X delivers more 'field usable lumens' for optical engineers to work with. Lumileds attention to beam angle, field angle, color over angle and optical efficiency gives engineers more lumens to work with and better quality of light than has been previously possible," said Alvin Yeoh. The result is an outdoor fixture with leading optical properties and exceptional efficiency.

LUXEON HL2X enables customers to meet the requirements of DLC Premium V5.1, enabling fixture manufacturers to access the best utility rebates while reducing energy consumption. The low thermal resistivity substrate, <2.6 °C/W, shrinks the size of heatsinks and simplifies the thermal design of fixtures. Superior color over angle – <40 pts – ensures high uniformity in the application.

Lumileds' LUXEON HL2X provides superior color over angle and low thermal resistance in a standard 3.5 × 3.5 mm 3535 package

The LUXEON HL2X is available in a standard 3.5 × 3.5 mm (3535) 3-stripe footprint, which is optically compatible with the popular LUXEON TX LED, enabling a low touch upgrade. The LUXEON HL2X is immediately available across a wide range of color temperatures from 2700 K to 6500 K and 70 CRI. LUXEON HL2X 80 CRI and 90 CRI options for indoor applications will be introduced in the coming months.

With the LUXEON HL2X, Lumileds continues our long history in pushing the state-of-the-art in high power emitters and furthers our commitment to the Illumination market. ■

Cree's Breakthrough Solution for LED Message Signs

The CV94D family are SMD RGB LEDs designed for the most demanding variable message displays. Manufactured to Cree's exacting standards of power, longevity, matched sub-pixel brightness and far field optical distribution, these LEDs outperform all existing SMD LED solutions. The CV94D is IPx6/IPx8 spray and water resistant in a 9.4 × 4.2 mm PLCC6 package.

SMD RGB LED – CV94D family

This SMD LED features an IPx8 water resistant rating in a PLCC6 package. These high performance tricolor SMT LEDs are designed to work in a wide range of applications.

The encapsulation resin contains UV inhibitors to minimize the effects of long-term exposure to direct sunlight, resulting in stable light output over the life of the LED. This PLCC6 package has an increased package height to ease in the manufacturing process. ■

Repro-light Consortium Deliver Intelligent Optics

Bartenbach's interdisciplinary team this week announced the successful engineering of two unparalleled optic designs. Driven by the scope of the Repro-light project, "To successfully initiate transformation in the European LED lighting industry, by creating the 'Luminaire of the Future'." Bartenbach was tasked to deliver a novel optical system, and is pleased to present two new "LED Light Tile Optics (LLT)".

Bartenbach, who is known for developing sophisticated optical systems, has designed an only 8.3 mm thick unique "LED Light Tile Optics (LLT)" for the Repro-Light project

The concept comprises a modular system allowing unlimited configuration, and light distributions within the fixture. At only 8.3 mm thick the LLT can easily be integrated in the light exit plane of many fixtures. Through using total internal reflection, light emitted by the LED is dispersed evenly over the whole tile and precisely radiated following a desired light intensity distribution. Therefore, high luminance outside the radiation field and multi-shadowing are avoided.

The patented design of the reflectively coated micro-facets ensures targeted, even distribution of light. Each facet is therefore calculated individually for total optimized light control. Depending on the chosen design of the facets, almost any desired light distribution can be achieved without the need to change the visual appearance of the tile. This unique light point composition across the facets, creates a consistent luminous surface with no multi-shadowing and also with no color shadowing when using two different colored LEDs, since they are perfectly mixed within the tile.

All LLTs with varying light intensity distributions are designed for the same LED position and share the same outer dimensions. Therefore, the same fixture can be used in different applications, by simply replacing an LLT to give an alternative desired light distribution. Tiles with different distributions can be mixed within one luminaire, for example, to generate ambient light and task light from the same luminaire.

Specifically for the Repro-light project, two types of tiles were created: a special batwing-distribution for task light, avoiding reflective-glare, and a wall wash distribution to generate large area ambient light. The downlight with batwing distribution can be both symmetrical and asymmetrical, i.e. the left part of the luminaire shines to the right and vice versa. Additionally, as light is distributed from the right and left optics there is no reduction of light directly underneath. When utilized together they harmoniously accomplish the following: reduced reflective glare, color mixing, elimination of multi shadowing, and are fully flushed.

In terms of application there are no limits: office, general illumination, hospitality, gastronomy, residential, outdoor and also within the Personal Table Light, which is engineered and designed by Bartenbach. The variation possibilities are also endless: singlepoint, multipoint (linear/panels), single function, multifunction, recessed, semi recessed, surface mounted, suspended, freestanding and table mounted.

"At Bartenbach we are very excited to have engineered an innovative optic design that adapts and works so flexibly across many environments, and we are proud to be part of the Repro-light consortium". Christian Anselm, Director Development

The development team is continually pushing boundaries and shaping the future of lighting with meticulous engineering. Bartenbach is famed for its innovation and creation of stunning lighting solutions. Notably, the James Bond cinematic experience in Soelden, Austria and the Airbnb Headquarters in Ireland.

For additional information on the Repro-light project, please visit `https://www.repro-light.eu/` ■

Epistar and Lextar to Jointly Establish A New Holding Company

Epistar Corporation ("Epistar" or the "Company") (TAIEX: 2448) and Lextar Electronics Corp. ("Lextar" or the "Company") (TAIEX: 3698) announce the two companies will jointly establish a holding company A (tentative name) via share conversion, which was approved in the board of directors' meetings of Epistar and Lextar.

Instrument Systems: New Spectroradiometer CAS 125 Speeds Up LED Production Testing

The CAS 125 spectroradiometer with CMOS sensor is designed to maximize production testing efficiency of LEDs. It offers a unique recipe mode for time-optimized control. Through parameterization of successive measurements, reading times of 0.01 ms become feasible. A built-in temperature stabilization ensures long-term stability even in environments where temperatures fluctuate.

www.instrumentsystems.com

Instrument Systems
KONICA MINOLTA Group

The share conversion ratios of the two companies are tentatively set at one share of Epistar for 0.5 ordinary share of company A, and one share of Lextar for 0.275 ordinary share of company A. Acting as III-V semiconductor investment platform, Company A is committed to flourishing current businesses of Epistar and Lextar and exploring advanced technologies for applications including mini/micro-LED display, intelligent sensing and III-V semiconductor microelectronics fields. While the company A will lead to strengthen the global competitiveness of both companies, Epistar and Lextar will operate independently and there will be no impact on their respective customers and employees.

Expertise, collaboration and synergies to complement and optimize efforts are the basis for the companies for creating a new milestone in the III-V compound semiconductor industry

Expertise, Collaboration, and Synergy

The synergy of this collaboration includes the following: (1) to integrate the resources and to refocus expertise of two companies. In the new era, Epistar will focus on LED upstream and midstream technology with Lextar becoming one of its valuable customers and Lextar will concentrate in-depth on downstream technologies with Epistar being one of its strategic suppliers, (2) to reinforce the connection between resources and product/technology development for faster commercialization, and to maximize the benefit with efficient investment and cost management, (3) to urge the application of mini/micro-LED technology to benefit customers, partners and consumers.

In the future, the two parties will jointly create a new milestone in the III-V compound semiconductor industry through this collaboration.

Focus, Complement and Optimization

Dr. B.J. Lee, Chairman of Epistar, said in terms of display application, LED technology has to not only win out in the competition, but also widen the gap to be ahead of other competing technologies within the shortest time. In other words, at this critical moment, the LED industry needs more collaboration than ever. In the future, company A will manage and plan overall operation to leverage the resources effectively and to develop the collaboration strategy for the industry in a macro view so all subsidiaries of company A can evolve on this platform. Patrick Fan, President of Epistar, said that Epistar will continue to concentrate on the upstream and midstream of LED to provide better products and services in this collaboration while Lextar will focus on the downstream products and become one of Epistar's important customers. This will not only contribute to the overall supply chain, but also accelerate the application development, so that consumers can enjoy the advantage of miniaturization of LED that can improve visual quality of displays for daily life.

Dr. David Su, Chairman and CEO of Lextar, said that the products of Lextar span the upstream, midstream and downstream of the industry. The company has not only the talents of each process platform, but also the capability of T.E.M.P. (Thermal, Electrical, Mechanical, Photo-electrical) integration. In the same time, Lextar has the advantage of retaining downstream customers and being close to the market. As the deepening of the collaboration, Epistar will become a strategic partner of Lextar for LED dies and Lextar will focus on the development of packaging and modular technologies to provide prompt services to worldwide customers.

Company A will integrate the advantage of Epistar and Lextar to create synergy in the collaboration. We believe company A will bring more values to the desires of mini/micro-LED display and 5G ecology in the future, thus generating a positive contribution to shareholders' rights and interests of both companies.

About Epistar Corporation:
Since founded in 1996, EPISTAR has been concentrating on the R&D and manufacturing activities of LED epi and dies products. Having accumulated tremendous expertise and profound knowledge, the ability of R&D and manufacturing, and the advantage of full-spectrum product portfolio, EPISTAR is able to satisfy customers' various demands and becomes a leading brand of global LED dies supplier. EPISTAR has gone through several M&A and cross licenses with first-tier LED companies, and its revenue in 2019 is NT 15.96 billion. In 2018, EPISTAR spun off three major business units. Based on its core technologies, EPISTAR extends its footprints from LED to different fields incorporating III-V semiconductor compound. Therefore, its roadmap has been expanding from "Actualize LED Potential" to "Actualize III-V Semiconductor Potential". – www.epistar.com

About Lextar Electronics Corp:
Lextar Electronics Corp. (TAIEX: 3698), founded in 2008 in Taiwan, specializes in manufacturing opto-semiconductor epitaxial, chips, packages, modules and integrated solutions. The range of applications includes LCD backlighting, R/G/B display, automotive lighting, professional lighting, sensing and UV. The company now houses around 3,500 employees and its headquarters is in the Hsinchu Science Park, Taiwan. Lextar has two manufacturing sites in Taiwan, and two in China, which are Chuzhou and Suzhou respectively. Lextar's turnover in 2019: USD 300 million. – Lextar.com ■

SMART & IOT

DALI Alliance Achieves Landmark of 1,000 DALI-2 Products Certified

The Digital Illumination Interface Alliance (DiiA), the global industry organization for DALI lighting control, announces its DALI-2 certification program has passed another milestone with the addition of the thousandth DALI-2 certified product to the organization's online product database.

DALI-2 certification involves rigorous testing and independent verification of test results, which gives confidence in cross-vendor product interoperability. Reaching this landmark, a feat achieved in less than three years since DALI-2 was first introduced, underscores the importance of DALI-2 in the lighting control market.

“The very rapid growth in certification of DALI-2 lighting control products shows no sign of slowing.”

PAUL DROSIHN, GENERAL MANAGER AT DIIA

“The progress we’ve seen to date reflects the advocacy shown by the global lighting industry. We are immensely grateful for the hard work of our members in recent years to help achieve this significant landmark in such a short span of time”, said Mr. Drosihn.

DALI-2 delivers more product types and features, clearer specifications and increased testing, compared with first generation DALI products. In addition to LED drivers and other control gear, the list of certified DALI-2 products includes application controllers (devices that make decisions and send commands), bus power supplies, and input devices, which provide user-derived and environmental information to the lighting-control system.

DALI-2 passed the 1000th product certification landmark gaining increased popularity

The thousandth product certified by the organization was an LED driver from DiiA founder member Tridonic. The organization’s product database now contains almost 2,400 products in total, including more than 1,350 first-generation DALI products from a broad range of members.

The DiiA anticipates further growth in DALI-2 certification, as new features and function are added to the program. For example, the first D4i LED drivers were recently added to the database, as well as the first DALI-2 tunable white LED drivers. ■

CALI and Zhaga Sign Liaison Agreement – To Drive and Promote Technology Advancement

The past decade has witnessed the LED evolution in the China lighting industry as well as progress in the work of Zhaga in standardizing interfaces of components of LED luminaires. Zhaga and CALI have identified areas of mutual interest and agreed to structure and strengthen their relationship and to foster closer cooperation through a liaison agreement. Consequently, the China Association of Lighting Industry (CALI) and the Zhaga Consortium (Zhaga) have signed a liaison agreement which entered into force on May 1st, 2020.

This fruitful cooperation will serve the global lighting market with better technologies, products and services

“Standing at the 10th anniversary of Zhaga, CALI is very happy to sign a strategic cooperation liaison with the Zhaga Consortium, which is committed to enhancing communications and cooperations of both parties on LED technologies, standards and ecosystems. Our member companies will benefit considerably from this cooperation”, said Mrs. WANG Zhuo, Secretary General of CALI.

“The Zhaga smart interface specifications will have an impact on the value of the lighting infrastructure for connectivity in China. This liaison agreement will drive innovation in sensor/communication modules incorporating new smart applications and will benefit the CALI and Zhaga member-ship.”

DEE DENTENEER, SECRETARY GENERAL OF ZHAGA

The development of this fruitful cooperation will serve the global lighting market with better technologies, products and services.

About CALI:

The China association of lighting industry (acronym: “CALI”), founded in 1989, is a nationwide, non-profit social organization of lighting industries in China. CALI is officially registered in Beijing under the supervision of the Ministry of Civil Affairs. CALI has branch committees to deal with multiple professional sectors of the lighting industry, including 12 professional committees, 3 working committees and 1 technical committee. CALI’s major business covers statistics, analysis, and prediction of lighting industry; establishing and revising related standards; providing recommendations to government on industrial development planning and policies etc. CALI is also actively connected with foreign lighting organizations and carries out international cooperations.

About Zhaga:

Zhaga is a global association of lighting companies that is standardizing interfaces of components of LED luminaires, including LED light engines, LED modules, LED arrays, holders, electronic control gear (LED drivers), connectors and sensor and/or wireless communication modules. This helps to streamline the LED lighting supply chain, and to simplify LED luminaire design and manufacturing. Zhaga continues to develop specifications based on the inter-related themes of interoperable components, smart and connected lighting, and serviceable luminaires. ■

New DLC Report: Interoperability for Networked Lighting Controls

Interoperability for Networked Lighting Controls explores the current interest in networked lighting controls (NLC) and the benefits various stakeholders can attain from championing interoperable systems. The report details three specific and actionable use cases and explains why interoperability is a core component for ongoing operation of energy savings programs and is essential for the long-lasting relevance of NLCs. At the end of each use case, the report outlines the steps lighting stakeholders can take to move the industry toward a more interoperable future.

Building systems, including Networked Lighting Control (NLC) systems, increasingly need to cooperate and communicate with other systems beyond their boundaries to achieve a higher level of operational efficiency and energy savings. The ability to exchange actionable information between two or more systems is called “interoperability”. Interoperability among building systems is the key enabler for unlocking benefits from cross-system operation and optimization.

This report describes the need for NLC interoperability and the ways that interoperability can improve outcomes for building owners, operators, and other key stakeholders. It provides a foundation of common understanding about NLC interoperability by clarifying:

- The definition of interoperability
- The importance of interoperability for energy savings and other value-added services it enables
- The barriers, opportunities, and value propositions associated with greater interoperability for various stakeholder groups

The goal of this report is to illustrate how the broad topic of interoperability can be addressed by focusing on use cases with specific stakeholder value, market barriers, technical gaps, and necessary supportive interventions. Three use cases are explored in depth, and the methodology is described so that this approach can be applied to additional use cases in the future. ■

UV LIGHT

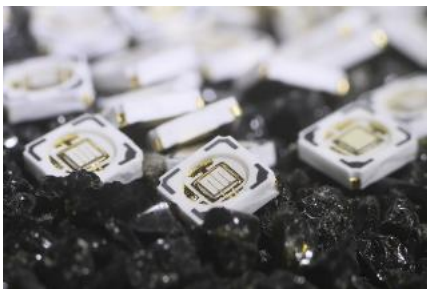
IES and IUVA Collaborate to Publish ANSI Standards for Measuring Ultraviolet C-Band (UV-C) Sources Used for Disinfection

The Illuminating Engineering Society (IES, est. 1906) and the International Ultraviolet Association (IUVA, est. 1999) have partnered to assemble experts in the measurement of ultraviolet C-band emissions (UV-C) to develop American National Standards for the measurement and characterization of UV-C device performance. UV-C devices for healthcare and personal care have proliferated in recent years, particularly during the COVID-19 pandemic, despite the absence of standards to enable accurate measurements and comparisons of the products. Through this partnership IES and IUVA aim to cooperatively promote awareness of and improve the application of ultraviolet "disinfection" technology in the healthcare system, initially through the development of standardized methods of measurement of ultraviolet "disinfection" products including UV lamps, luminaires and lighting/radiating systems, utilizing both discharge (e.g. low-pressure mercury and xenon) and solid-state (e.g. light-emitting diode) technologies.

Annually 99,000 people are estimated to die from healthcare-associated infections (HAIs) in the United States alone, more than 11 people per hour. HAIs are also estimated to result in USD 10B in direct medical costs annually and up to USD 147B in total societal costs. UV-C emissions are known to cause photochemical damage to nucleic acids and proteins, inactivating and thus rendering pathogens incapable of reproducing. UV-C disinfection devices are therefore useful in healthcare settings to reduce patient and healthcare worker exposure to these pathogens when combined with standard cleaning strategies. To enable broader UV-C adoption, healthcare administrators need credible and comparable product performance data to inform investments for both new construction and retrofits.

A series of American National Standards (ANSI standards) are envisioned, beginning with two slated for publication by year's end. The first standard, Approved Method for Electrical and Ultraviolet Measurement of Discharge Sources, will detail laboratory procedures for the measurement and characterization of low-pressure mercury and other discharge sources. The second, Approved Method for Electrical and Ultraviolet Measurement of Solid-State Sources, will do the same for UV-LED components.

IES Director of Standards and Research Brian Liebel said "The Illuminating Engineering Society is dedicated to developing standards and providing educational content on UV-C to help reduce the number of healthcare-associated infections and the transmission of pathogens, such as the SARS-CoV-2 virus. Working with the International Ultraviolet Association, we feel confident that our organizations can effectively deliver much-needed measurement and testing standards to evaluate new products as they come to market."



UV LEDs and especially UV-C LEDs have greatly improved in the last years. The two organizations aim to develop American National Standards for the measurement and characterization

"IUVA, through its Healthcare/UV Working Group, has been working on developing industry consensus-based standards for UV disinfection since 2018. Establishing this partnership with IES is a key component of making that happen," said Troy Cowan, the IUVA Working Group's Coordinator. "We needed representation of the entire lighting sector to build industry-consensus, and IES delivers that. Thanks to IES' and IUVA's collaborative efforts, these new ANSI standards will eliminate much of the ambiguity and uncertainty in UV output measurement. This will improve accuracy and quality, and give the healthcare industry a credible basis for assessing output of UV disinfection devices for the first time." ■

Signify Invests to Broaden Its UV-C Lighting Portfolio for Professional Disinfection

Signify, the world leader in lighting, is increasing its UV-C lighting production capacity and expanding its UV-C product portfolio. The company is leveraging more than 35 years of expertise in UV-C lighting to address the growing global need for the disinfection of air, surfaces and objects.

By increasing capacity and broadening the UV-C portfolio, Signify is helping keep people safe in a world that's adjusting to a new normal. Its UV-C lighting is well-proven and trusted as an effective disinfectant. This was recently validated in a laboratory test by Boston University, showing that Signify's UV-C light sources inactivate the virus that causes COVID-19 in a matter of seconds. This is crucial as it comes at a time when organizations are seeking ways to continue operations and provide service in a safe environment.

Signify's new UV-C product range includes luminaires and chambers for a wide variety of professional applications.

"We have introduced 12 families of UV-C lighting fixtures specifically designed to disinfect air, surfaces and objects. These products target different customer segments ranging from offices, schools, gyms, retail stores, warehouses, as well as on public transport." Explains Harsh Chitale, leader of Signify's digital solutions division.

UV-C light sources can inactivate the COVID-19 virus within seconds. Signify's new UV-C product range includes luminaires and chambers for a wide variety of professional applications

Part of the range are UV-C fixtures which are ideal for the deep disinfection of surfaces in offices, schools and restrooms. They are equipped with sensors and controls to ensure that they only operate when people and animals aren't present. Other products include mobile, freestanding UV-C luminaires that can be wheeled into a hotel room or used to disinfect surfaces on public transport such as buses and trains.

For the disinfection of objects, Signify launches a range of safe and quick-to-use UV-C disinfection chambers. These chambers are used in offices and municipal buildings to disinfect visitor tags, phones, bags, laptops and wallets in a matter of seconds. In stores they're ideal for disinfecting returned items, glasses or clothes tried on in a changing room.

UV-C fixtures can also be used inside surface disinfection tunnels. In North America a large retailer is piloting a UV-C tunnel for disinfecting shopping trolleys. In India, a hotel plans to use a Signify UV-C tunnel for disinfecting guests' bags at check-in.

To complement its portfolio, Signify recently acquired the assets of Germicidal Lamps & Applications (GLA), a small, Netherlands-based company with extensive expertise in UV-C disinfection solutions. The deal includes GLA's upper-room UV-C air disinfection portfolio as well as deep application knowledge.

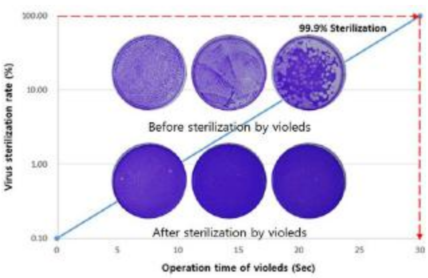
Paul Peeters, leader of Signify's digital solutions Europe, emphasizes: "The assets and know-how acquired from GLA will help us to accelerate the development of our roadmap of UV-C based upper-room air disinfection systems. We plan to make these products available across the world soon."

The upper-room air disinfection luminaires can be used with people in the room, as they are installed at a height which, in combination with shielding and optics, prevents exposure to the UV-C light source. Air in the upper part of the room is constantly disinfected using UV-C irradiation and natural convection of airflow in the room. This makes these perfect for use in schools, offices, gyms, retail outlets and other high-contact areas.

For more than 35 years, Signify has been at the forefront of UV technology, and has a proven track record of innovation in UV-C lighting. Signify's UV-C lighting is designed, installed, and used according to the product-specific safety instructions, and manufactured using well-controlled industrial processes. ■

Global Lighting Association Releases Safety Guidelines for UV-C Disinfecting Devices

The Global Lighting Association has issued a Position Statement containing guidelines for the safe use of UV-C devices. The statement concerns safety and standardization requirements.



While being a useful tool to defend germs and pathogens of any kind, considering the safety requirements for UV-C emitting products are most important (Image Credits: Seoul Semiconductor)

Germicidal ultraviolet irradiation is a proven methodology for inactivating viruses on solid surfaces, in water and in air. As such it is expected to be a useful tool in the fight against the COVID-19 pandemic. UV-C is a category of ultraviolet light with wavelengths between 100–280 nanometers and is the most effective UV light for disinfection.

While UV-C is helping to contain viruses, if not used properly it can pose risks to human health. GLA is concerned at the proliferation of UV disinfecting devices – particularly being sold on the internet – with dubious safety features and inadequate safety instructions.

Standardization bodies are expected to develop comprehensive standards for the safe operation of UV-C devices. However, this process will take many months, if not years. In the interests of public safety, as an interim measure the Global Lighting Association has brought together industry experts and developed guidelines to assist users and manufacturers pending publication of these standards.

Position Statement on Germicidal UV-C Irradiation: UV-C Safety Guidelines may be downloaded from the Global Lighting Association's website. ■

GKT's New UV-C Board Combines LEDIL's "VIOLET" and NICHIA's "NCSU334A"

In these turbulent times, we need reliable disinfection. Large amounts of water or large areas must be disinfected quickly within a few seconds. GKT offers a new design for this. Based on the new LEDIL "VIOLET" UV-C 12× multibeam lens, we have combined with the also new UV-C LED "NCSU334A" from NICHIA.

The combination of LEDIL's "VIOLET" and NICHIA's "NCSU334A" for an UV-C board makes it an efficient and powerful tool for reliable and fast disinfection

The result of the combination of LEDIL and NICHIA is a circuit board that has 660 mW relevant UV-C output at a wavelength of 280 nm. The current consumption is typical 350 mA at 62 volt input voltage. An NTC for temperature measurement is also on-board, so the LEDs can be overdriven to a higher current limit. The boards can be connected in series. ■

HORTICULTURE

Active Grow Launches UL Listed LoPro Max Horticultural Luminaires for Commercial and Home Growers

Active Grow, the sustainable horticultural lighting manufacturer, is proud to announce the launch of its LoPro Max 640 W and 320 W horticultural luminaires. These lightweight, UL Listed fixtures conveniently replace 600–1000 W and 400–600 W HPS lights in vertical racking or sea of green commercial applications, using nearly half the energy and producing half the heat. The concealed-driver design means no messy cabling or bulky external drivers. The ultra-thin profile (just 2.47") allows the luminaires to go to work in spaces with minimal vertical clearance. Integrated dimming and a tool-less installation make these fixtures perfect options for home growers with tents or hydroponic benches.

Active Grow's LoPro Max luminaires may replace HPS solutions thereby being up to almost two times as efficient

Each luminaire comes standard with the Active Grow Entourage Spectrum which is optimized to boost growth during both vegetative and flowering cycles by incorporating additional Far-Red 730 nm wavelengths. These Far-Red wavelengths combine with 660–680 nm wavelengths to increase plant photosynthesis rates via the Emerson effect which results in faster grow cycles, enhanced flavonoid content and a higher percentage of trichomes in cannabis. The natural high CRI 94 light also makes plants look more vivid, making inspection and maintenance of plants easier.

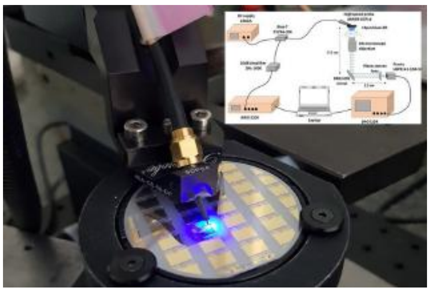
The LoPro Max luminaires utilize Philips chipsets for maximum light output and proprietary optics that create uniform light coverage and deep canopy penetration for high DLI requirement plants. The slim form factor and 4–8 bar design allows the fixtures to be placed safely above plants in low height applications without burning the canopy. The 640 W and 320 W luminaires feature typical PBAR (280–800 nm) outputs of 1644 µmol/s and 822 µmol/s respectively, giving each an exceptional efficacy of 2.6 µmol/J. The built-in 0–10 V rotary dimmer lets growers adjust the light output from 10–100% without the need for additional wiring or installation.

Active Grow builds each fixture using IP65 rated components to withstand the rigors of tough CEA environments. The proprietary SafeShield optic creates a thermal buffer to protect the LED diodes from overheating, guaranteeing a 50,000-hour lifetime. Both versions use premium universal voltage drivers, can be daisy chained on 120 V, 240 V and 277 V circuits and come with a 5-year warranty. For larger installations, the luminaires can be used with wireless grouping control systems (up to 100 fixtures). ■

RESEARCH

CEA-Leti Researchers Break Throughput Record for LiFi Communications Using Single GaN Blue Micro-LEDs

CEA-Leti recently announced its researchers have broken the throughput world record of 5.1 Gbps in visible light communications (VLC) using a single GaN blue micro- light-emitting diode (LED). Their data transmission rate of 7.7 Gbps achieved with a 10 µm microLED marks another step toward commercialization and widespread use of LiFi communication.



Using blue LEDs, data-transmission rate of 7.7 Gbps positions LiFi as possible replacement for WiFi. Inset: CEA-Leti testbed for single GaN blue microLED that achieved the throughput record

VLC, commonly called LiFi (short for "light fidelity"), is an emerging wireless communication system that offers an alternative or a complementary technology to radio frequency (RF) systems such as WiFi and 5G. It is considered to be a promising technology for security-related applications because light propagation can be confined to a room with no information leakage, as opposed to WiFi communication, which penetrates walls. LiFi also holds promise for ultra-highspeed data transmission in environments where RF emissions are controlled, like hospitals, schools, and airplanes.

Single microLED communications offer an ultra-high data-transmission rate for a variety of opportunities for new applications. These include industrial wireless high-speed links in demanding environments such as assembly lines and data centers, and contact-less connectors, or chip-to-chip communication. But their weak optical power limits their applications to short-range communications. In contrast, matrices of thousands of microLEDs contain higher optical powers than open mid- and long-range applications. However, preserving the bandwidth of each microLED within a matrix requires that each signal has to be brought as close as possible to the micro-optical source.

Exciting Potential for Mass-Market Applications: CEA-Leti's expertise in the microLED epitaxial process produces microLEDs as small as 10 microns, which is among the smallest in the world. The smaller the emissive area of the LED, the higher the communication bandwidth – 1.8 GHz in the institute's single-blue microLED project. The team also produced an advanced multi-carrier modulation combined with digital signal processing. This high-spectrum-efficiency waveform was transmitted by the single LED and was received on a high-speed photodetector and demodulated using a direct sampling oscilloscope.

"This technology has the exciting potential for mass-market applications."

BENOIT MISCOPEIN, CEA-LETI RESEARCH SCIENTIST

"Multi-LED systems could replace WiFi, but wide-scale adoption will require a standardization process to ensure the systems' interoperability between different manufacturers. The Light Communications Alliance was created in 2019 to encourage the industry to implement this standardization."

In addition to a stand-alone WiFi-like standard, the possibility to include this new technology as a component carrier in the downlink of 5G-NR, a radio-access technology for 5G mobile considerations, is also under investigation to bring a large additional license-free bandwidth.

"This may be feasible because CEA-Leti's LiFi physical layer relies on the same concepts as WiFi and 5G technologies," said Miscopein. "Matrices of thousands of microLEDs could also open the way to mid- to long-range applications, such as indoor wireless multiple access."

Preserving the bandwidth of each microLED within a matrix requires that each signal is generated as close as possible to the micro-optical source.

“To meet this challenge, we expect to hybridize the microLED matrix onto another matrix of CMOS drivers: one simple CMOS driver will pilot one microLED,” Miscopein said. “This will also enable the additional feature of piloting each microLED pixel independently, and that allows new types of digital-to-optical waveforms that could eliminate the need for digital-to-analog converters commonly used in the conventional ’analogue’ implementations of LiFi.” ■

Printed Perovskite LEDs – An Innovative Technique Towards a New Standard Process of Electronics Manufacturing

A team of researchers from the Helmholtz-Zentrum Berlin (HZB) and Humboldt-Universität zu Berlin has succeeded for the first time in producing light-emitting diodes (LEDs) from a hybrid perovskite semiconductor material using inkjet printing. This opens the door to broad application of these materials in manufacturing many different kinds of electronic components. The scientists achieved the breakthrough with the help of a trick: “inoculating” (or seeding) the surface with specific crystals.

A look inside the Helmholtz Innovation Lab HySPRINT. Major work on the printable perovskite LEDs was carried out here (Credits: HZB/Phil Dera)

Microelectronics utilize various functional materials whose properties make them suitable for specific applications. For example, transistors and data storage devices are made of silicon, and most photovoltaic cells used for generating electricity from sunlight are also currently made of this semiconductor material. In contrast, compound semiconductors such as gallium nitride are used to generate light in optoelectronic elements such as light-emitting diodes (LEDs). The manufacturing processes are also different for the various classes of materials.

Transcending the materials and methods maze

Hybrid perovskite materials promise simplification – by arranging the organic and inorganic components of semiconducting crystal in a specific structure. “They can be used to manufacture all kinds of microelectronic components by modifying their composition”, says Prof. Emil List-Kratochvil, head of a Joint Research Group at HZB and Humboldt-Universität.

What’s more, processing perovskite crystals is comparatively simple. “They can be produced from a liquid solution, so you can build the desired component one layer at a time directly on the substrate”, the physicist explains.

First solar cells from an inkjet printer, now light-emitting diodes too

Scientists at HZB have already shown in recent years that solar cells can be printed from a solution of semiconductor compounds – and are worldwide leaders in this technology today. Now for the first time, the joint team of HZB and HU Berlin has succeeded in producing functional light-emitting diodes in this manner. The research group used a metal halide perovskite for this purpose. This is a material that promises particularly high efficiency in generating light – but on the other hand is difficult to process.

“Until now, it has not been possible to produce these kinds of semiconductor layers with sufficient quality from a liquid solution,” said Emil List-Kratochvil, Professor of Hybrid Devices at the Humboldt-Universität Berlin.

For example, LEDs could be printed just from organic semiconductors, but these provide only modest luminosity. “The challenge was how to cause the salt-like precursor that we printed onto the substrate to crystallize quickly and evenly by using some sort of an attractant or catalyst”, explains the scientist. The team chose a seed crystal for this purpose: a salt crystal that attaches itself to the substrate and triggers formation of a gridwork for the subsequent perovskite layers.

Significantly better optical and electronic characteristics

In this way, the researchers created printed LEDs that possess far higher luminosity and considerably better electrical properties than could be previously achieved using additive manufacturing processes. But for List-Kratochvil, this success is only an intermediate step on the road to future micro- and optoelectronics that he believes will be based exclusively on hybrid perovskite semiconductors. “The advantages offered by a single universally applicable class of materials and a single cost-effective and simple process for manufacturing any kind of component are striking”, says the scientist. He is therefore planning to eventually manufacture all important electronic components this way in the laboratories of HZB and HU Berlin.

References:

List-Kratochvil is Professor of Hybrid Devices at the Humboldt-Universität zu Berlin and head of a Joint Lab founded in 2018 that is operated by HU together with HZB. In addition, a team jointly headed by List-Kratochvil and HZB scientist Dr. Eva Unger is working in the Helmholtz Innovation Lab HySPRINT on the development of coating and printing processes – also known in technical jargon as “additive manufacturing” – for hybrid perovskites. These are crystals possessing a perovskite structure that contain both inorganic and organic components.

The work was published in Materials Horizons, the journal of the Royal Society of Chemistry, in an article entitled “Finally, inkjet-printed metal-halide perovskite LEDs – utilizing seed-crystal templating of salty PEDOT:PSS” by Felix Hermerschmidt, Florian Mathies, Vincent R. F. Schröder, Carolin Rehermann, Nicolas Zorn Morales, Eva L. Unger, Emil J. W. List-Kratochvil. ■

TECHNICAL REGULATORY COMPLIANCE UPDATE

Segment	Product	Standard (Certification)	Region	Technical Regulatory Compliance Information
Energy Efficiency	LED products for indoor lighting	GB 30255-2019	China	This standard specifies technical requirements, test- and calculation methods and minimum allowable values of energy efficiency for non-directional self-ballasted LED lamps for general lighting. The standard will enter into force on first November 2020 and will repeal GB 30255-2013. It was already published on 4th of April 2019 and affects LED-lighting which is used in an idoor environment.
Energy Efficiency	LED luminaires for road and tunnel lighting	GB 37478-2019	China	This standard is meant for LED luminaires for road and tunnel lighting. It specifies requirements for energy grades, color rendering, test methods and minimum values regarding energy efficiency for LED luminaires for road and tunnel lighting. It applies to LED luminaires for road and tunnels with rated voltage of 220 V AC / 50 Hz, including LED control devices, excluding interconnected control components that can be installed independently or other functional accessories not related to lighting. It was published on 4th of April 2019 by SAC and SAMR. It will enter into force on first of November 2020.
Safety	Lighting products	IEC 63129:2020 Edition 1.0 (2020-04-21)	World/Europe	Determination of inrush current characteristics of lighting products.
Safety	Organic light emitting diode (OLED) light sources for general lighting	IEC 62868-1:2020 Edition 1.0 (2020-05-14)	World/Europe	Organic light emitting diode (OLED) Light sources for general lighting – Safety – Part 1: General requirements and tests. This standard replaces the IEC 62868:2014 and sets the basic safety requirements for OLED products. It will be complemented by part 2's for the specific OLED product. It includes requirements for marking, construction, mechanical hazards, insulation resistance and electric stress, fault condition, thermal stress, Resistance to heat and fire and photobiological safety.
Safety	Organic light emitting diode (OLED) light sources for general lighting	IEC 62868-2-1:2020 PRV Edition 1.0 (2020-06-12)	World/Europe	Organic light emitting diode (OLED) light sources for general lighting – Safety – Part 2–1: Particular requirements – Semi-integrated OLED modules. This standard sets the specific safety requirements for **semi-integrated** OLED products using the IEC 62868-1 as basis for the safety requierments. It is for voltages up to 120 V DC or 50 V AC at 50/60 Hz. Covered are integral, built-in or independent OLED modules.
Safety	Organic light emitting diode (OLED) light sources for general lighting	IEC 62868-2-2:2020 PRV Edition 1.0 (2020-06-12)	World/Europe	Organic light emitting diode (OLED) light sources for general lighting – Safety – Part 2–2: Particular requirements – Integrated OLED modules. This standard sets the specific safety requirements for **integrated** OLED products using the IEC 62868-1 as basis for the safety requirments. It is for voltages up to 1000 V DC or 1000 V AC at 50/60 Hz. Covered are integral, built-in or independent OLED modules.
Safety	LED modules for general lighting	EN IEC 62031:2020 DOW: 2022-12-18	World/Europe	LED modules for general lighting – Safety specifications. The IEC 62031:2018 was adopted as EN version without modification replacing EN 62031:2008/A2:2015. With this version a revision of the marking of the working voltage, terminals, heat management, definitions according to the replacability and information for luminaire design were introduced.
Performance	Controlgear for LED modules	IEC 62384:2020 Edition 2.0 (2020-05-13)	World/Europe	DC or AC supplied electronic controlgear for LED modules – Performance requirements. This standard replaces the IEC 62384/AMD1:2009. It is now suitable to be used to 100 V DC/AC. It includes new specifications or measuring the power factor for controlgear with settable/non-constant output (for instance, to allow for constant light output), improvement for the selection of the test circuit load and deleted the audio frequency requirments.

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Designing with Dynamic Light Textures – Enlightening Designers

Light takes just a short moment to travel from one point to another and to reach our eyes. Always immersed in the experience of light, we tend to take this for granted.

This thesis provides the reader with the necessary theoretical frameworks to understand the research aimed towards answering the question: which associations do people have with atmospheres influenced by dynamic light textures? This question is then used to provide a framework of guidelines for the designer. A review of lighting design history introduced the terms ambient luminescence, focal glow and play of brilliants proposed by Kelly (Kelly, 1952). Research into perceptual psychology then disentangled principles of perception to the reader, after which it was found that mood was commonly used to measure the impact of environments. Contradictory results of studies suggested that mood lacked a reliable method of measurement. In a study by Vogels (Vogels, 2008), introducing the term atmosphere as a stable alternative for mood, defined as the affective evaluation of the environment, was introduced. In this study, the impact of static light conditions on atmosphere perception was investigated. It was found that four underlying variables are of influence when perceiving environments with static light conditions: cosiness, liveliness, tenseness and detachedness. Focusing on dynamic light conditions, a distinction was made between using real-world or abstract dynamic patterns as stimuli. The way people perceive real-world scenes was found to vary depending on culture and background (Nisbett & Miyamoto, 2005) (Kuwabara & Smith, 2016), leading to the preference for abstract patterns. A translation of abstract patterns into dynamic light textures was made by considering the principle of ensemble perception. Inspired by the natural world 39 stimuli were created. Participants were subjected to these stimuli in an experiment, finding that participants use the same words when describing atmospheres influenced by dynamic light textures through a frequency analysis. Participants' responses were clustered according to their meaning, resulting in a 40 word lexicon. A set of 13 stimuli were shown to 16 participants in a second experiment, and participants' responses were recorded using a questionnaire containing the 40 word lexicon. It was found that participants gave relatively the same responses. Additionally, it was found through a principal component analysis that three underlying variables are present in the perception of atmospheres influenced by dynamic light conditions: tenseness, liveliness and detachment. Furthermore, it was confirmed that people are able to distinguish between the perceived atmospheres. Cosiness was not found to be a principal component in our construct. Regarding the workings of the underlying variables found, we found that liveliness is influenced by organisation of shapes in the texture and colour contrasts. Tenseness is influenced by the complexity of individual forms within textures; it is also influenced by colour contrasts. Brilliance contrasts in the texture influence liveliness of a space; sharpness contrasts influence the sense of detachment. Dynamics in the textures, like the rate of change, influence both the liveliness and tenseness axes and might influence the detachment axis. The findings of the experiments and analyses were used to develop a framework usable by designers, noting however that several points of recommendation were made to improve the reliability and usability of this framework. ■

Subjects

- Atmosphere
- Atmosphere perception
- Lighting design
- Light texture
- Light
- Dynamic lighting
- Perception
- Perceptual psychology atmosphere metrics
- Principal Component Analysis

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Tech-Talks BREGENZ Scott ZIMMERMAN, Founder and Chief Research Officer (CRO) of Silas, USA – “REACTIVE OXYGEN SPECIES”

Scott ZIMMERMAN
Scott Zimmerman has over 30 years experience and 85 issued patents in the area of lighting and displays. With the help of a number of researchers around the world, he has combined optical modeling from the lighting community and electron spin resonance data from the medical community to show three dimensionally how the body has evolved an amazing array of bio-optical mechanisms in the skin, brain, eyes, and fetus. This understanding is being used to develop healthier light sources and improved NIR sources for cancer treatments.

Scott Zimmerman has been inestigating the effects of visible and invisible light radiation for several years. He previously published an article in LED professional that presents a technology that adds a sufficient amount of Near Infrared ratiation (NIR) to artifical light to provide a positive effect on health. In another research article entitled, “Melatonin and the Optics of the Human Body”, Zimmerman and Reiter (1) discussed how health is impacted by all wavelengths in sunlight, and that, when talking about health and well-being, not just lumens/watts are relevant, but instead, the Reactive Oxygen Species (ROS) density and antioxidant respnse as a function of wavelength becomes important. The paper discussed how the human body uses ROS to kill pathogens, heal wounds, control hormone levels and bolster the immune system, espcialy in the UV and NIR. Because of the ongoing COVID-19 crisis, LED professional was motivated to discuss these and other findings with Scott Zimmerman.

LED professional: **You are known for not avoiding controversial discussions on health and artificial light. Could you tell us a little about how you got the idea of specializing in the topic of invisible light, especially NIR and health and well-being? We’d also be interested in hearing a little about SILAS and your company.**

Scott ZIMMERMAN: I noticed that the NIR exposure levels used in phototherapy sessions to increase blood flow and accelerate wound healing were on par with the NIR levels we are exposed to in sunlight and even a well-lit incandescent room. Being a numbers guy, I wanted to quantify this effect. What we know is that when photons are absorbed in our cells they generate directly or indirectly Reactive Oxygen Species (ROS) and in many cases it is the ROS that stimulates a biological response that is good or bad. That is what is in the paper with Prof. Reiter. From a perspective standpoint it is like peeling a layer off an onion. Once you move beyond just counting photons and begin to understand how those photons are creating ROS three dimensionally in the body, you see some amazing bio-optical mechanisms that the body has developed over millions of years of adaptation. It also makes it clear that the body assumes it is exposed to a single predominately NIR emitter, the Sun. That forms the rationale behind Silas IP and products. Silas is a small privately funded company focused on two areas, artificial environments and control systems that mimic the entire solar spectrum and an enhanced NIR hyperthermia source for cancer treatments. Based on this viewpoint, when COVID-19 struck I looked at what role ROS might be playing from a germicidal and therapeutic standpoint. Like my previous work, I was amazed at how little we knew.

LED professional: **You recently sent me the draft of an article with the title “Could Reactive Oxygen Species be why Influenza is Seasonal?”. If it’s okay with you, I’d like to talk in detail about that, and perhaps dig a little deeper.**

Scott ZIMMERMAN: Of course, it is my pleasure. Please feel free to ask whatever you want. I just want to make it clear that this is not a silver bullet but an attempt to stimulate a broader discussion. The medical community is appropriately focused on vaccines and therapeutic drugs. Our industry is a key part of defining the artificial environment that protects our medical workers, be it UV disinfection, circadian, or something else.

LED professional: **In your article you emphasized the fact that “a flu season does not just happen. Understanding the root cause of why many pandemics end based on season and return the following season, is at least as important as vaccines and therapeutic drugs.” Are you the first person to recognize this? Is there any evidence pointing to a reason for it?**

Scott ZIMMERMAN: No, I am not the first to recognize seasonality and it has been studied off and on for decades. We still do not know why it occurs. In fact, my motivation to work in this area comes from a quote from Dr. Dowell, the Deputy Director of Epidemiology and Surveillance, Vaccine Development for the Bill and Melinda Gates Foundation, who says: “If we knew what suppresses influenza to summertime levels, this would be a lot more effective than any of the flu vaccines we have.”

That is a shocking statement, especially when you include into his statement Tuberculosis and other airborne diseases that exhibit seasonality. If you look at the seven influenza epidemics between 1945 and 1975, 90% of the deaths occurred from Nov to April [2] The reality is that most epidemics and pandemics in temperate climates start and stop based on the seasonal changes with and without vaccines. Near the equator, there is less seasonality. I believe that nature knows something we do not.

Furthermore, in the March 25th Coronavirus Task Force briefing, Dr. Fauci NIAID Director at NIH indicated that he suspects COVID-19 is seasonal, given the data now coming out of the southern hemisphere countries. That means COVID-19 will probably be back.

Seasonality can easily be observed and is well documented. Increased person to person contact, lack of Vitamin D, decreased humidity, and animal experiments suggesting that viruses prefer cool and dry conditions have all been put forth as root causes. But we still experience seasonal flu every year. I believe this indicates that we are missing something.

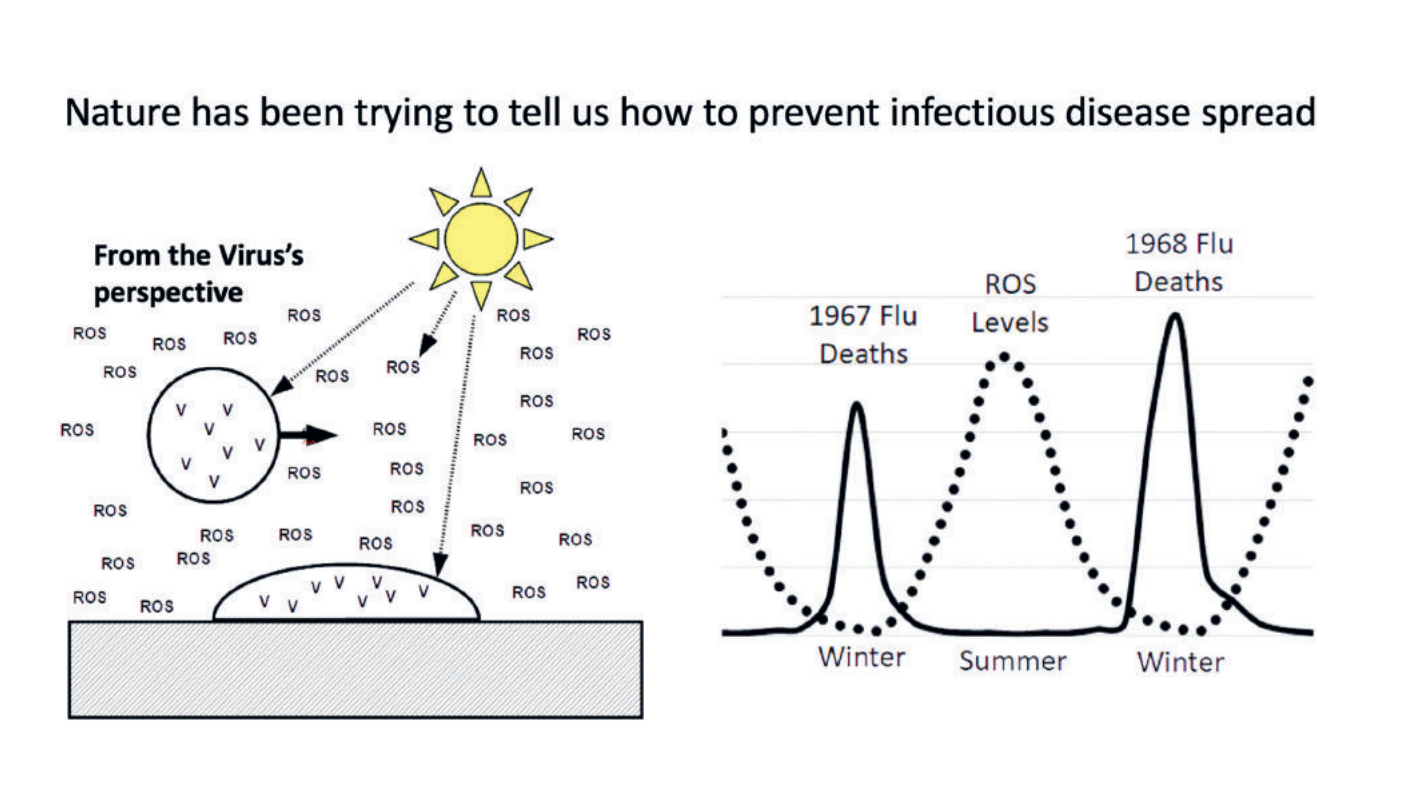

Figure 1: Sunlight generates germicidal levels of Reactive Oxygen Species (ROS) every spring/summer. If we can alter our artificial environment to mimic springtime levels in the fall, we may be able to stop epidemics before they start

LED professional: Do you have an idea of what it is that we're missing? Does it have anything to do with ROS?

Scott ZIMMERMAN: Yes, it is a hypothesis but from a ROS perspective, I would point out some facts.

The Sun generates germicidal levels of ROS in the spring and summer months at higher latitudes and year-round near the equator in fresh air. We know these levels are germicidal because similar levels of ROS like hydrogen peroxide have been used by the disinfection industry to kill viruses and germs for decades.

We also know that simultaneously, absorbed solar radiation from about 250 nm to over 3000 nm increases as we wear lighter clothing, expose more skin to sunlight, and we spend more time outdoors. We know that this stimulates increased ROS production in the body, which in turn stimulates our immune systems.

Enclosed spaces with heating and/or air conditioning, man-made air pollution, stagnant/dry air, Low E glass, extended periods of darkness, heavy snowfall, and rainy seasons all tend to locally deplete these naturally occurring ROS levels.

I am suggesting that flu season starts because low ROS levels favor the pathogens while flu season stops because higher ROS levels favor the host (us). Recent experiments appear to support this hypothesis.

In March, the NIAID COVID-19 aerosol data showed that in dark filtered dry air the virus has a half-life of over one hour [3], [4] (Half-life is the time it takes for 50% of the virus particles to be inactivated. Longer half-life equals more opportunity for disease spread). In April, DHS aerosol experiments exposed the COVID-19 virus to filtered Xenon arc lamps combined with humidified air. The half-life of the virus dropped to 90 seconds [5]. Two decades ago, Marsden showed that flu viruses in a sneeze droplet traveling through 10 ppbv hydrogen peroxide atmosphere had a half-life of under 10 milliseconds [6]. Springtime air has a hydrogen peroxide level of up to 5 ppbv with fall levels dropping to less than a few hundred pptv in the fall and winter [7].

Two thirds of the people who were infected in NYC were sheltering in place. It may be possible to reduce this number.

LED professional: The term, Reactive Oxygen Species, or ROS, is the main topic of your article. I'm pretty sure that the average person doesn't know much about it. Before we go on, could you please expalin what it is, what effect is has on our bodies and why it is so important?

Scott ZIMMERMAN: Reactive Oxygen Species is a general term for both free radical and oxidizing species such as hydroxide, nitric oxide, ozone, hydrogen peroxide, etc. There are a host of ROS that occur naturally in the air we breathe and water we drink. In the work you referenced with Reiter, we showed that the entire solar spectrum (250 nm to over 3000 nm) is generating huge amounts of ROS in our cells every second in exposed skin. Significant amounts of NIR photons even penetrate clothing. Unlike photons, ROS have half-lives that range from a few nanoseconds to days allowing them to accumulate, be stored, and dispersed, which makes them very useful in biological processes. We also know that the body generates its own ROS (hydrogen peroxide) as a killing response by immune cells and nasal cells to microbial attacks and pollution ([8], [9]). Recent evidence has shown that ROS play a key role as a messenger in normal cell signal transduction and occurs naturally in cellular energy production [11],[12] . But despite their beneficial activities, overproduction of Reactive Oxygen Species during times of environmental stress can also be toxic to cells. Too little ROS is bad, too much ROS can be very bad, and in-between is essential for life. It is, as so often, a question of the dose.

Our body and the virus live in an atmosphere that has always been filled with ROS. The second figure I sent is a simple illustration on the virus scale of what the atmosphere looks like. Sunlight generates a gauntlet of ROS through which the virus must pass. Cough droplets containing thousands of virus particles are absorbing millions of ROS molecules as they move, and droplets on surfaces are surrounded by ROS. These naturally occurring germicidal effects are happening continuously and on a global scale.

I believe and there is scientific evidence, that during wintertime, there is not enough ROS in the air and not enough ROS being produced in our body.

We have the technology to mimic these effects on a widespread basis in the fall and winter, if we can quantify the impact and provide cost effective practical solutions. The lighting, HVAC, and architectural industries will have to make this happen, as the medical research community is already overwhelmed. This, however, will require our industries to follow the same rules as the medical industry: Clinical trials, peer review, FDA approval, etc.

LED professional: You're talking about mimicking Nature by using improved, artificial light – but what is it that happens in Nature?

Scott ZIMMERMAN: As already mentioned, the entire solar spectrum from 100 nm to over 3000 nm is impacting our health. All the UVC and most of the UVB is absorbed in the atmosphere, generating a huge reservoir of naturally occurring ROS. The UV that makes it through the atmosphere produces Vitamin D in our skin, but also is absorbed in a very thin layer of the outer skin generating very high ROS density that creates a killing field for pathogens trying to enter the body, while still supporting the healthy microbiome

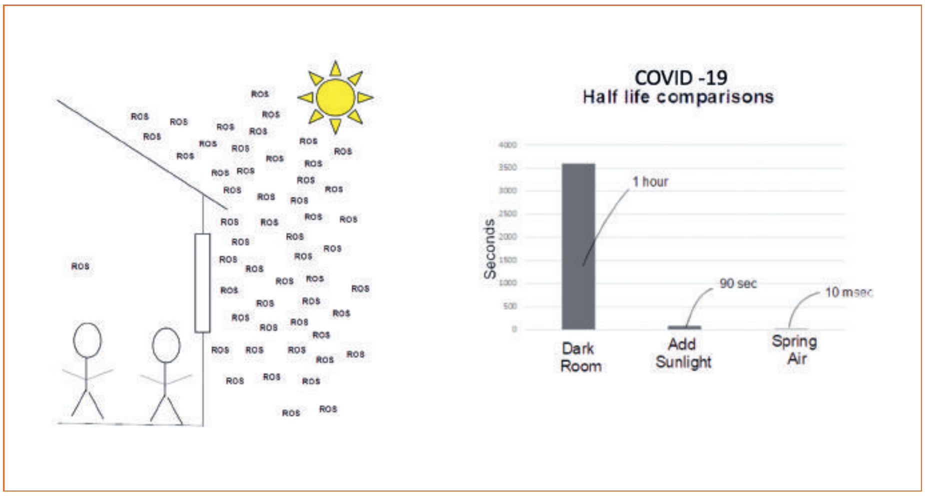

Figure 2: Lack of fresh air exchanges, heating/cooling, and filtration of sunlight in our enclosed spaces reduce ROS levels promoting infectious disease spread. The path of least resistance for any virus is now where we live, work, and learn

that lives on the skin. From ESR data and optical models we know that in sunlight the visible (400 nm to 650 nm) generates just as many ROS as are generated in the UV. But based on the optics of the skin, the ROS are distributed into cells up to 1 mm deep below the surface. Around 650 nm there is a rapid decrease in the optical absorption creating "biological windows" between 650 nm and 2000 nm that allow for penetration in excess of an inch to occur. This creates some amazing bio-optical effects.

As an example, the body assumes it is exposed to the Sun. UV and HEV photons have enough energy to randomly break molecular bonds. To survive, the body provides a sacrificial outer dead skin layer containing a host of beneficial micro-organisms, melanopsin in the skin absorbs visible photons causing the release of antioxidant beta carotene from white fat cells [12] and NIR photons penetrate deep into the body inducing vasodilation by releasing ROS (nitric oxide compounds) throughout the entire microcapillary network coincident and proportional to amount of UV damage being generated [13]. The increased blood flow removes the waste products created by the higher energy photons and increase the white blood cell count to just the damaged area. This is an example of only one mechanism that we know of.

In nature we are never exposed to UV/Visible without an excess of NIR. That is no longer true for our artificial environment and we have virtually zero research into what happens long term when you eliminate 80% of the solar spectrum. Right now, we have the perfect storm: LEDs provide only 400 nm to 700 nm, mandated energy savings windows block NIR from entering our homes and less than 10% of our time is spent in sunlight.

There is also another point that I want to mention in this respect. As I have shown, children and high melanin level individuals are uniquely impacted by sunlight. Because of their smaller size, almost 100% of the cells in a child "see" at least some portion of the solar spectrum, especially in the NIR, compared to less than half in adults. Also, important to know, the black population require more sunlight to produce the same level of Vitamin D and receives less than 30% of the NIR (impacts ROS levels in the body) than the white population does. We need to measure basic optical properties for all skin types to understand how the entire solar spectrum impacts the health of especially the black population at higher latitudes.

LED professional: What do you say to the fact that ozone levels in some areas in the summer reach undesirably high levels? How can you be sure that the figures you are referring to are not artificial – too high due to air pollution – and therefore don't harm our bodies, but actually support health?

Scott ZIMMERMAN: Naturally occurring ROS unfortunately gets lumped in with man-made ROS (air pollution, water pollution, etc.). Ironically, studies done for the Beijing Olympics showed that man-made ROS such as sulfur dioxide from coal and cars virtually eliminated hydrogen peroxide in the city compared to readings on a local mountain [14]. A historical study of the 1918 pandemic proposed that much higher mortality rates in urban versus rural areas correlated to air pollution levels from urban coal fired plants [15].

It is hard to separate out man-made effects from natural effects. That is why this discussion is so important to have now. In the mist of this tragedy we have a unique opportunity to look at disease spread. As satellite measurements show, air pollution levels are plummeting and quarantine is limiting seeding rates. But we need to know which causal variables to look for. That is why I appreciate LED Professional and you for being willing to put this out there.

LED professional: In a recent article you used the terms "atmospheric ROS", "liquid ROS" and "solar ROS". You also mentioned variations, especially in H_{202} levels, during the year. Can you explain what "atmospheric ROS" is and why the variations may be relevant?

Scott ZIMMERMAN: The sun generates three basic types of naturally occurring ROS. Atmosphere ROS are in the air we breathe and the environment that viruses must travel through to infect their next host. Liquid ROS are in the water we drink and in the various forms of water and water vapor (lakes, clouds, fog, humidifiers, etc.). Solar ROS are generated when photons from the Sun are absorbed by biological cells (our body, viruses, microbiome, etc.).

Regarding atmospheric ROS, we have known for a long time that many ROS types [16], but especially hydrogen peroxide levels in the air, vary with the seasons. H_2O_2 levels are up to seven times higher during the spring and summer than in the fall and winter. Hydrogen peroxide levels in our surroundings range from near zero in dark stagnant air to over 300 ppbv in snowflakes ([17], [18]). The majority of hydrogen peroxide and other ROS are generated by UV photons interacting with the atmosphere, evaporation from lakes/rivers, rainfall, and from plant photorespiration ([19], [20], [21]).

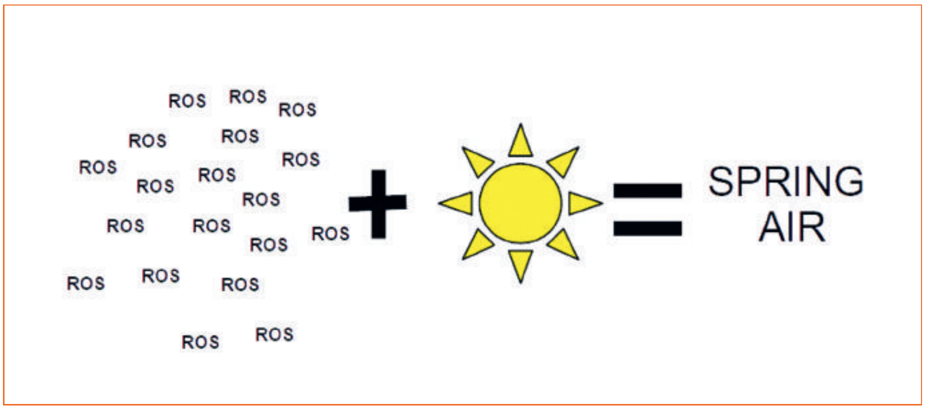

Figure 3: We can generate low-level germicidal reservoirs in our enclosed spaces that mimic spring air. This minimalistic immersion approach to disinfection is inherently safe, more effective than intermittent cleaning with toxic chemicals, and reduces virus exposure compared to in-duct solutions. To really mimic nature indoors will require changes to how we do HVAC, lighting, and sensors.

LED professional: Do these findings show evidence of the variations during the year affecting our health?

Scott ZIMMERMAN: Yes, we think so. Based on the work of RGF Inc. and Prof. Marsden we know that 10 ppb hydrogen peroxide kills over 99% of viruses in the air, and low-level hydrogen peroxide and other ROS types have been used for over 20 years in a variety of disinfection applications with over a million systems sold [22]. This data shows atmospheric ROS, for instance, impacts the number of viable virus particles in a cough. While the existing theory is that influenza prefers cool and dry conditions, from a ROS perspective cool and dry conditions simply contains less ROS resulting in the virus being able to travel further. Unfortunately, existing cough models ([23], [24]) do not consider the cumulative effects of passing through a ROS laden atmosphere. Consider the impact on viral spread.

Let me take the example of cough and let me give you some rough figures on this: When we sneeze or cough, we project up to 40,000 droplets ranging in size from less than a micron to over 100 microns in diameter containing hundered million virus particles (roughly 5000 virus particles per droplet) . As the RGF Environmental Group states, 10 ppb of hydrogen peroxide is still 1.7×10^{20} molecules per liter [25]. This means, assuming uniform distribution, that each molecule of hydrogen peroxide is separated three dimensionally in space by approximately 1 micron. A 10-micron water droplet traveling three feet could accumulate almost 100 million hydrogen peroxide molecules as it traverses the distance. Following Marsden, who has shown that using 10 ppb of hydrogen peroxide kills 99% of the virus, in the time a cough takes to travels three feet, the virus particles in the droplet would have a half-life of less than 10 millisecond, as I mentioned earlier. I want to point it out again, that the levels of hydrogen peroxide by Marsden and RGF are occurring naturally every spring and summer but not in the fall and winter and at higher latitudes.

LED professional: That sounds quite solid. Is there anything more you would like to say about it or can we talk about liquid ROS and solar ROS?

Scott ZIMMERMAN: I could talk the rest of our time just about atmospheric ROS, but I think the essence of the findings is visible in the given example and I really want to give a good and comprehensive overview. So, I would prefer to take the next step to liquid ROS.

In simple terms, we know that hydrogen peroxide accumulates from rainfall, snowfall, and photobiological processes in lakes and rivers and reaches its peak levels in the spring and summer months. Hydrogen peroxide, combined with ozone, is also used in some water treatment facilities to replace chlorine. Hydrogen peroxide can have a half-life of over 10 days in water, so the tap water that we drink and the tap water we use in humidifiers in many cases contains significant amounts of ROS. As we drink water, we are essentially disinfecting our airways. Companies are now developing nebulizer-based drug treatments to stimulate our cells to release increased levels of ROS in our airways to kill

COVID-19 virus particles [26]. Nature just got there first. Ironically, the clear plastic bottles that we buy most likely decompose any natural ROS present at bottling. A study done by Mayo a few years back showed that just increasing the humidity using cyclone humidifiers and tap water (with ROS) cut flu absentees by 50% in classrooms [27]. This year's flu vaccine was estimated to be 45% effective.

I just want to explain solar ROS very briefly as your readers might already know most facts from my article in LpR66 – March/April 2018 issue. What has occurred since then is a deeper appreciation for how sunlight is interacting with not just our body but the virus as well. As we talked about earlier, the NIAID and DHS data provides an excellent baseline for COVID-19 that the lack of sunlight increases the ability to spread in dark wintertime conditions. DHS has the capability to study the relative impact of UV, VIS, and NIR as well as introduce various ROS types and levels to their carrier gases. Silas has requested that both groups run these tests so that the HVAC, lighting, and architectural industries can design systems that actively suppress disease spread. Silas has also requested that MIT and other disease spread modeling groups include ROS in their models to better understand how relative motion impacts the half-life of the virus both indoors and outdoors.

Finally, Burnett gave an excellent talk recently concerning possible negative impact of UV (UVC, UVB, UVA, UVV) being sold by our industry [28]. From a ROS perspective, nature has specifically chosen to not take the "kill everything" approach our industry is pursuing. Instead Nature is choosing to use continuous low level naturally occurring ROS germicides and foster the microbiome on our skin, disinfect our airways, and stimulate our immune systems. The EPA defines a disinfectant as generating a 6log kill (99.9999%) which, by definition, requires the use of chemicals that not only kill the virus but also the microbiome in our skin [29]. I would suggest that we first consider taking full advantage of what nature provides.

LED professional: It almost sounds too good to be true. Am I correct in thinking that a simple formula can increase our level of health? Or is it more difficult to mimic nature and maintain summertime infection rates year-round, than it seems?

Scott ZIMMERMAN: The problem is, that this is a preventive measure, not a shot, pill, or treatment. Ask the Mayo group how hard it is to get a humidifier mandated into all classrooms even though it might cut the flu cases in half. To be fair, it is easier to run clinical trials for a vaccine than to scientifically prove the efficacy of more fresh air exchanges in nursing homes. In Nature during spring and summer, the air we breathe is killing germs, the water we drink is killing germs, and sunlight is killing germs on our skin and stimulating our immune system all at the same time. This does not happen – or at least not that much – in the winter, or in our homes or offices.

To mimic nature, all three of these ROS effects need to occur simultaneously, be ubiquitous, and be within a tightly controlled range to be effective and safe that can get past multiple government regulations that focused only on energy savings.

Based on this evidence, we need our artificial environment to provide a ROS atmosphere, we need to drink and humidify our homes with unpolluted water containing naturally occurring levels of ROS, and we need ultraviolet to infrared sources that stimulate Vitamin D and all the other bio-optical mechanisms, especially in the NIR (increases ROS levels in body) during the fall and winter. We have all the elements to do this. Rather than focusing all our research just on better sleep, it may be time to look deeper and admit that our industry can be much more than what we see with our eyes. One pandemic has cost more than all the energy savings LEDs could have realized in 100 years. Sunlight is our baseline, and the deeper we dig, the more we find that our bodies are using all of it, not just the part we see with our eyes.

LED professional: COVID-19 is a hot topic right now. Do you have findings regarding the pandemic?

Scott ZIMMERMAN: The recent COVID-19 pandemic brought us an explosion of UV disinfection equipment that may help, but there are serious concerns that it should always still be used in combination with chemical treatments such as hydrogen peroxide [30]. We found that nature provides not only UV/VIS/NIR disinfection and a natural low-level ubiquitous germicide based on a wide range of ROS types, but also forms a protective germicide on and in our skin as it stimulates a higher antioxidant response, in the spring and summer. I am convinced that we need to learn from nature and use these tools throughout the year. While we have multiple methods to kill viruses and germs, they do not lend themselves to widespread usage. As with social distancing and handwashing, to make a maximum impact it needs to happen everywhere. We all breathe, drink, and should enjoy the sunlight.

Like most pandemics, we have no immunity to this specific virus yet. It however is still transmitted using the same mechanisms as the flu. Unlike a vaccine or therapeutic drug, understanding how nature has stopped pandemics may be generic. What about the next COVID virus outbreak? Are we going to shut down the world economy again? What I believe seasonality tells us is that something generic and global in nature changes and that change is capable of both starting and stopping most pandemics. I have proposed one explanation based on ROS.

ASHRAE mandates a minimum of 0.35 air changes per hour in homes to reduce body odors, two air changes per hour in nursing homes again for odors, and 12 air changes per hour with three "fresh" air exchanges in operating rooms to prevent anesthesia buildup based on a 50-year-old equation that incorrectly assumes that all air is the same ([31]).

LED professional: Does this mean that Mother Nature has always used the best practice methods – at least in spring and summer – and we should follow her example?

Scott ZIMMERMAN: Do not get me wrong! While I am convinced that naturally occurring ROS is strongly suppressing disease spread, I am not saying this is a magic bullet. Transmission via direct contact can occur in any environment. But I absolutely believe that we can use ROS to reduce disease spread. Why? Let me again give you some numbers that might help make the invisible visible: As we discussed earlier, a single sneeze can propel roughly 40,000 droplets with a couple hundred million virus particles in the droplets. For COVID-19 it has been estimated that between 100 to 1000 virus particles need to make it into the airway to infect someone (as few as one particle for Tuberculosis). As you can see in Figure 2 that compares NIAID, DHS, and Marsden, the environment the virus is exposed to has a huge impact on how long the virus survives and how far it can propagate.

In Marsden's experiment, there are only 50 viable virus particles in each droplet in 100 msec and zero in less than a second. If we use the NIAID data, in an hour there are still 2500 viable virus particles in each droplet. If you are wearing an N95 mask with 10% side leakage, which environment would you choose to work in?

However, there is still a lot of work to do. We need, for example, to quantify the benefit via clinical trials, produce low cost practical solutions, and act. If the trials show a real benefit – and this is not the time for marketing games – we need to develop solutions that can be implemented on a global scale. This will only work if we get widespread usage. The medical community will certainly find medical solutions, namely vaccines and therapeutics for COVID-19, using time-tested clinical trials and methods. But there might also come another virus – and for sure the next influenza season as it comes every year – and we need any help that we can get.

LED professional: The COVID-19 pandemic shows that we need all the help we can get. There is still a long way to go and a lot of work to do – but it would certainly be worth doing more research in the direction you are going to find a solution. Since we're running out of time, would you like to make a closing statement?

Scott ZIMMERMAN: Yes, of course. I can just support what you said right before. Most of the experimental data, modeling, and governing equations associated with infectious disease spread assumes air is air, water is water and that sunlight is only used to see. That is wrong. From a virus particle's vantage point, the path of least resistance is our homes, offices, schools, nursing homes, and even some hospitals, not outside on a sunny spring day. Contact tracing studies are beginning to support this statement. In a recent preprint one Japanese study indicates that we are over 18 times more likely to catch COVID-19 indoors compared to outdoors [32]. Does it stop a couple who are kissing from transmitting COVID-19? Absolutely not, but something in nature starts and stops most pandemics. Imagine if we could help prevent future outbreaks, or at least buy more time to develop medical solutions for the next bug. With existing technologies, we already have the ability to generate atmospheric ROS, liquid ROS, and solar ROS to mimicking what nature does naturally every spring and summer. Could there be other factors? Absolutely, but these factors are obvious and safe to test. As the medical community has typically focused on drug solutions, it will be up to us – the lighting and building community – to provide them with the safest artificial environment in which to work. Dr. Dowell's statement is really a challenge that we need as an industry to take on because if we figure this out, we might be able to stop other infectious diseases now and in the future.

LED professional: Scott, many thanks for this interesting conversation. Stay safe and healthy.

Scott ZIMMERMAN: It was my pleasure. Thank you for the opportunity to talk about this important topic. ■

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Atomic Layer Deposition – Leading Thin Film Coating Technology for Solid State Lighting

Atomic Layer Deposition was invented in the 70's as a way of depositing conformal phosphor layers for electroluminescent displays. In the new millennium, it became a key enabler of microelectronic devices and is now an industry mainstay for DRAM, MEMS and NAND devices. Additionally, ALD offers many advantages for the production of display devices – LEDs, micro-LEDs and organic-LEDs. Picosun Group is a leader in applying ALD in the field of Optoelectronics and Picosun's Marketing Manager, Minna Toivola D.Sc.(Tech), will introduce this interesting technology, explain how it works, show its opportunities and applications and demonstrate its advantages over other coating technologies for similar applications.

Since LEDs were introduced to large-scale commercial use in the 1990's and early 2000's, they have revolutionized lighting and become a ubiquitous technology everywhere we go. From household lightbulbs, flashlights and mobile device displays to car lamps, TVs and large outdoor video screens, it is hard to imagine a world without LEDs.

Despite the obvious benefits, there is still room for improvement in LED brightness, efficiency and manufacturing costs, especially in demanding large volume, high power applications such as street lighting. LED chips and LED phosphors are also moisture-sensitive and small LEDs can be sensitive to high temperatures. These same attributes apply also and especially for emerging solid-state lighting (SSL) devices such as micro- and mini-LEDs, as well as OLEDs. A thin film coating technology called Atomic Layer Deposition (ALD) offers various solutions to the challenges in conventional LED, mini/micro-LED and OLED manufacturing. This article gives an overview of ALD, how it differs from other thin film coating methods, and what it can offer to SSL industries. The impact of implementing ALD to process flows of LED devices can be as significant as converting lighting from traditional to LED based, meaning increased energy efficiency, extended lifetime, cost savings and chip size reductions.

The Basics of ALD and Its Benefits Over Other Thin Film Coating Technologies

ALD is an advanced, sophisticated thin film coating method that, nowadays, is a mature, key enabling technology in all modern semiconductor device manufacturing. ALD was invented in Finland by Doctor of Technology, Tuomo Suntola, in 1974. Back then the technology was way ahead of its time and it took until the mid- 2000's when it was incorporated for the first time by Intel into transistor manufacturing. Since then, the utilization of ALD and the number of its applications have skyrocketed throughout the industrial field.

ALD belongs to the group of chemical vapor vacuum coating methods, but its film growth process differs from the more well-known techniques of the same family such as Chemical Vapor Deposition (CVD) or Physical Vapor Deposition (PVD). In ALD, the precursor chemicals from which the desired thin film material is formed are introduced to the reaction chamber in gaseous form as sequential pulses, separated by a period of purge with inert gas. In compound AB formation, precursor containing the A atoms reacts first with the object-to-be-coated by surface adsorption reaction, covering all available reaction sites. The A atoms stick to the surface and inert gas flushes off reaction by-products and excess precursor. Next, precursor containing the B atoms is introduced to the reaction chamber where it, in turn, reacts with the A atoms on the surface, forming the first layer of compound AB. Again, inert gas flushes the reaction chamber and the first ALD cycle is completed. These cycles are repeated till the desired film thickness is achieved and, as the thicknesses of individual atomic/molecular layers of the compounds are well-known, the total film thickness can be controlled with digital repeatability and accuracy (**Figure** 2). The typical ALD film thicknesses vary from a single atom layer to a few tens or hundreds nanometers.

Due to this self-limiting, surface-controlled film growth mechanism, ALD has various benefits over other thin film coating technologies, such as superior uniformity down to sub-nanometer levels and unmatched conformality even over nanoscale surface details such as deep trenches, voids, cavities and high steps (**Figure** 3).

In other methods such as CVD or PVD, the precursors are pulsed to the reaction chamber at the same time. This means that they react with each other already before hitting the surface, forming relatively thick films which are not uniform, cannot reach for example the insides of high aspect ratio trenches, and often contain mi-

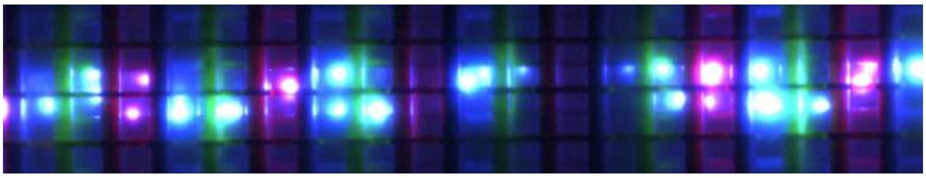

Figure 1: Micro-LEDs (image credit Picosun customer, Prof. Hao-Chung Kuo, NCTU Taiwan)

croscale cracks and pinholes. As ALD films grow "up" from the surface atomic layer by atomic layer, they are inherently dense, pinhole- and crack-free and their composition can be tailored down to atomic level. This makes it possible to create, in addition to single material layers, a plethora of mixed, doped and graded films, film stacks and nanolaminates. This allows endless opportunities for surface modification and functionalization with completely new electrical, optical or physical properties (**Figure** 4).

The list of materials that can be deposited with ALD is wide, the most typical being oxides, nitrides, sulfides, fluorides and metals (even noble metals and platinum-group metals can be deposited). Some of the most often used ALD materials, especially in semiconductor industries, are Al_2O_3, TiO_2, SiO_2, HfO_2, Ta_2O_5, ZrO_2, TiN and AlN.

ALD process temperatures are moderate, typically between 100–400 °C, which makes the method suitable also for temperature-sensitive substrates and devices. Using special techniques such as plasma-enhanced ALD (PEALD), some processes can be run even at close to room temperature. ALD does not need high vacuum, typically the processes take place at 1–10 hPa.

In ALD, film growth is slower compared to e.g. PVD or CVD, but the film quality compensates this. With ALD, the desired surface functionality can be obtained with much thinner films than in PVD or CVD, which also saves precursor materials and costs. For example, in barrier applications, ALD film can result in over ten times better barrier performance with one tenth of a barrier thickness compared with the same material deposited with plasma-enhanced CVD (PECVD) or PVD. Modern, industrial scale, fully automated batch ALD reactors can accommodate large numbers of substrates per run, which further diminishes manufacturing costs and allows fast, high volume production. As ALD is already a production-proven, routine method in other wafer-based semiconductor industries, it is easy to integrate to LED manufacturing as well (**Figure** 5).

ALD in Conventional LED Manufacturing

In conventional LEDs, the main applications of ALD relate to improving the LEDs' light extraction efficiency and the device lifetime and reliability. In these industries, ALD is already used in high volume manufacturing by several leading players.

Passivation Layers

ALD passivation layer on the LED surface "blocks" traps and defects which could cause leakage/parasitic currents. This improves light emission intensity. Superior performance and extremely low leakage current was achieved with Al_2O_3/SiO_2 ALD stack coating, compared to single layer SiO_2 deposited with PECVD method [1]. Both ALD Al_2O_3 and SiO_2 have near zero absorbance on visible light wavelengths which makes them especially suitable for surface passivation of lighting devices.

Figure 2: The principle of ALD film formation (image credit Picosun)

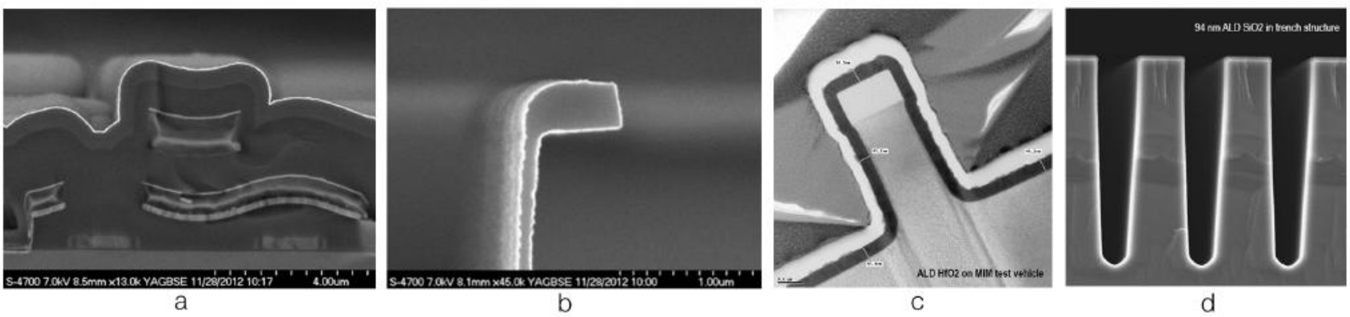

Figure 3: Examples of ALD films' excellent uniformity and conformality. SEM-micrographs a) and b): Conductive ALD layers on and inside MEMS (microelectromechanical system) structures (image credit Picosun customer Fraunhofer IMS, Germany); c) 45 nm ALD HfO_2 inside MIM (metal-insulator-metal) capacitor test structure (image credit Picosun); d) 94 nm ALD SiO_2 inside trench structure (images credit Picosun)

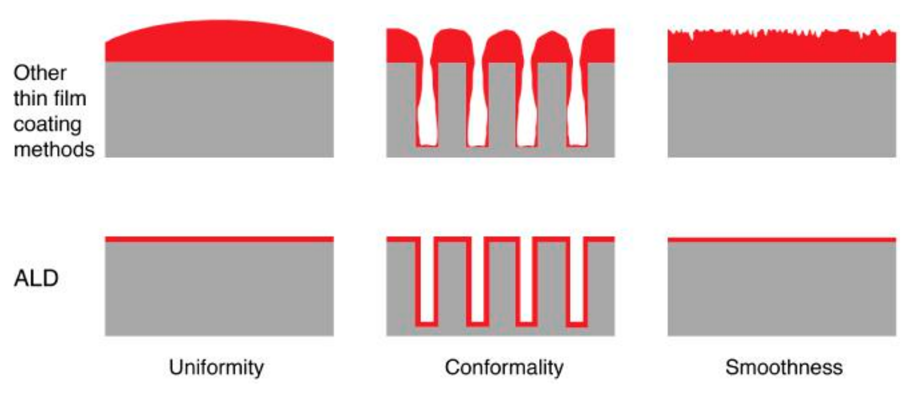

Figure 4: Benefits of ALD over other thin film coating methods (image credit Picosun)

Moisture Barrier Layers

ALD coating also works as a barrier layer against moisture and gases, thus improving LED lifetime and reliability. ALD ensures hermetic encapsulation against ambient conditions, with superior barrier performance compared to other methods. Typically, nanolaminates of various ALD oxides are used in this application. Employing a nanolaminate instead of a single-material layer gives extra protection by creating tortuous path for water molecule diffusion pathways caused e.g. by grain boundaries in the film.

Below two examples of Picosun's ALD films as moisture barriers:

Example 1:

- Reference: 330 nm PECVD SiO_2: water vapor transmission rate (WVTR) $\approx 10^{-3}$ g/m^2/d.
- Picosun's 40 nm ALD barrier layer: WVTR $= 2 \times 10^{-5}$ g/m^2/d (customer data, limited by measurement time).

⇒ ALD film exhibits 100× higher performance at 1/8 film thickness [2].

Example 2:

- Reference: PEN/PET: WVTR $\approx 10^{-1}$ g/m^2/d.
- Picosun's ALD nanolaminate: WVTR $= 4 \ldots 5 \times 10^{-5}$ g/m^2/d (customer data, limited by time and device glue life, not ALD film barrier properties).

⇒ ALD film exhibits 2000× higher performance compared to reference material [2].

ALD is an ideal method also for protecting moisture-sensitive LED phosphors against ambient conditions. ALD forms uniform, conformal, continuous and crack-free coating on each phosphor particle individually, without agglomeration or sintering. Ultra-thin ALD films are practically massless and dimensionless so they keep the particle size, weight and surface area close to original. ALD films do not decrease the amount of light emitted by the phosphors, or their quantum efficiency. ALD films can be deposited on both hydrophilic and hydrophobic surfaces, ceramic, metallic, and organic particles with sizes down to sub-micron range. As a gentle, gas-phase coating method with moderate process temperatures, ALD eliminates the risks for microscopic surface damage to the coated particles and makes the method suitable also for sensitive materials. Below third example of ALD's superiority as moisture barrier encapsulant in LED applications:

Example 3:

- Coated surface: LED phosphor powder, immediately unstable in air.
- Coating each grain of phosphor with a perfectly conformal ALD film of less than 40 nm thickness hermetically seals the grains' surface.

⇒ ALD-coated phosphor has lifetime over 1400 hrs at 100% RH / 100 °C [2].

Transparent Conductive Oxide Layers

Transparent conductive oxide (TCO) layers are applied as electrodes/current collectors on LEDs to distribute and deliver the electrical carriers into the structure. Typical TCO material in LED applications is indium-doped tin oxide (ITO), but due to the scarcity of indium metal, alternatives have been widely investigated. Aluminum-doped zinc oxide (AZO), which has high transmittance over visible wavelengths and which resistivity can be optimized by tuning the aluminium content and process temperature, is one potential candidate. ALD-deposited TCO layers in general are especially ideal for novel LED architectures where nanoscale surface patterning such as nanorods, -spheres or -pyramids have been employed to enhance the light extraction efficiency.

Figure 5: PICOSUN® P-300BV, an example of an ALD reactor developed specifically for LED applications (images credit Picosun)

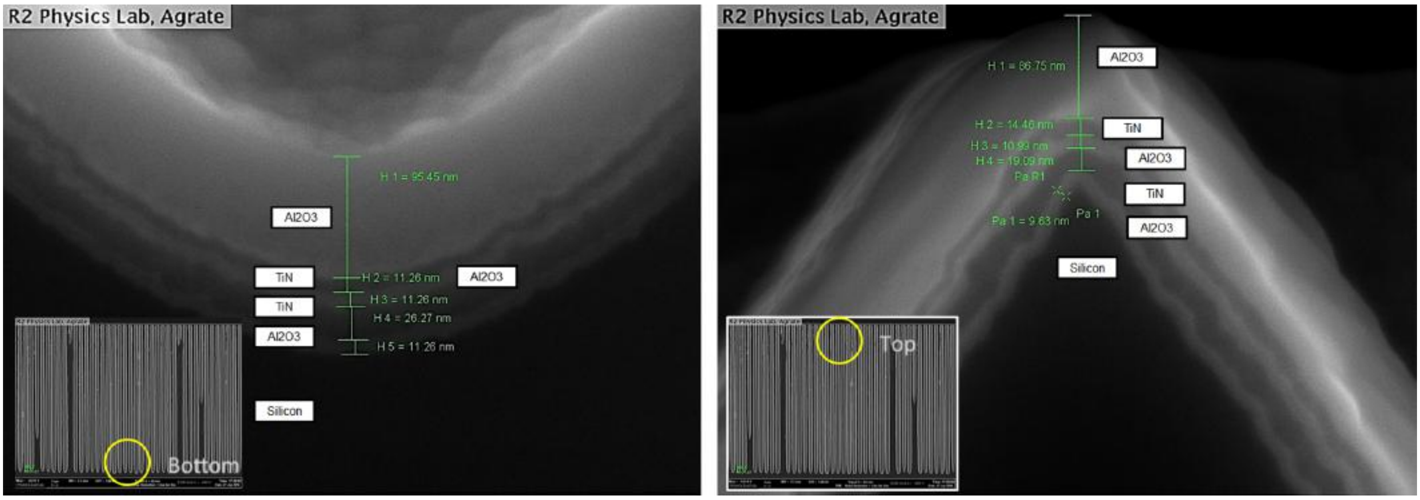

Figure 7: SEM-micrographs of highly conformal ALD Al_2O_3 – TiN – Al_2O_3 – TiN – Al_2O_3 nanolaminates in deep trench structures (images credit STMicroelectronics, Italy, in collaboration with Picosun in the EU-project "R2Power300")

Silver Mirror/Reflector Protection

Most LED designs employ thin silver film on the "bottom" of the LED stack to reflect back the light emitted towards the substrate. This improves the LED's brightness but the silver mirror is sensitive to tarnishing caused by moisture and chemical vapors. Also, especially under high electric fields, silver may start to diffuse to the neighbouring layers and thus degrade the LED performance. ALD thin film coating efficiently protects the silver from tarnishing and prevents silver diffusion.

ALD-coated LED reflectors have shown extreme durability even in high temperature acid vapor tests (HNO_3, 75 °C, 24 hours), due to the unmatched structural integrity and conformality of the ALD film [2]. Typical ALD materials used in this application are SiO_2, Al_2O_3, and their combinations. HfO_2 is also a potential candidate as it has excellent etch resistance even in extreme conditions.

Figure 6: Uncoated (left) vs ALD-coated silver mirror (right) aged four years at room temperature and moisture (image credit Picosun/Dr. Tero Pilvi, doctoral dissertation, University of Helsinki, 2008)

Optical Layers

Optical layers such as antireflection (AR) films and distributed Bragg reflectors (DBR) are often used in LEDs to improve light extraction efficiency [1]. ALD, with its superior uniformity, conformality, and the possibility to create atomic level tailored, multilayer film stacks with digitally repeatable layer thickness control down to sub-nanometer levels is an ideal method to manufacture optical coatings on non-planar samples and devices. ALD offers infinite possibilities to design optical stacks optimized for the desired wavelengths, just with varying the individual sub-layer materials and thicknesses. Some ALD films, for example AZO, can even combine two functions by acting both as the current collecting TCO layer and as the AR film (**Figure** 7).

Dielectric Insulation Layers

In semiconductor industries, especially transistor manufacturing, ALD has been used for years to deposit ultra-thin gate dielectric layers, thus promoting the constant miniaturization of the components. ALD's superior conformality and thinness can be utilized to deposit dielectric insulation for LEDs as well. For example, Al_2O_3/SiO_2 ALD dielectric reduces the thickness of the insulation layer and improves light extraction efficiency.

ALD's Specific Benefits for Mini- and Micro-LEDs

Mini- and micro-LEDs are new LED technologies that show significant potential as the enablers of future lighting and display solutions [3]. Micro-LEDs especially have excellent performance compared to other technologies such as liquid crystal or conventional LED displays, such as compact size, low power consumption, flexibility, fast response, ultra-high resolution, superior brightness and energy efficiency, and greater contrast and color saturation. Micro-LEDs are ideal for small displays in e.g. smartphones and smart watches, but high manufacturing costs and reliability issues have been the downsides of the technology this far.

Mini- and micro-LEDs are similar to the conventional LEDs when it comes to the operating principle and basic materials, but the manufacturing methods and structural details differ. Especially micro-LEDs are orders of magnitude smaller than conventional LEDs and they often employ microscopically patterned surfaces to maximize light output. Here, ALD shows again its beauty when ultra-thin functional or protective layers must be deposited evenly and conformally on these tiny surface details.

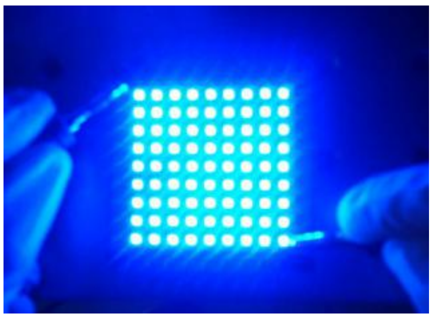

Figure 8: Flexible white mini-LED sheet (image credit Picosun customer, Prof. Hao-Chung Kuo, NCTU Taiwan) [4]

As the most of the ALD's applications in mini- and micro-LED manufacturing are analogous to those in conventional LEDs (passivation, moisture barriers, TCO films, optical layers, etc), this chapter highlights those uses where ALD has exceptional benefits just for these emerging LED technologies.

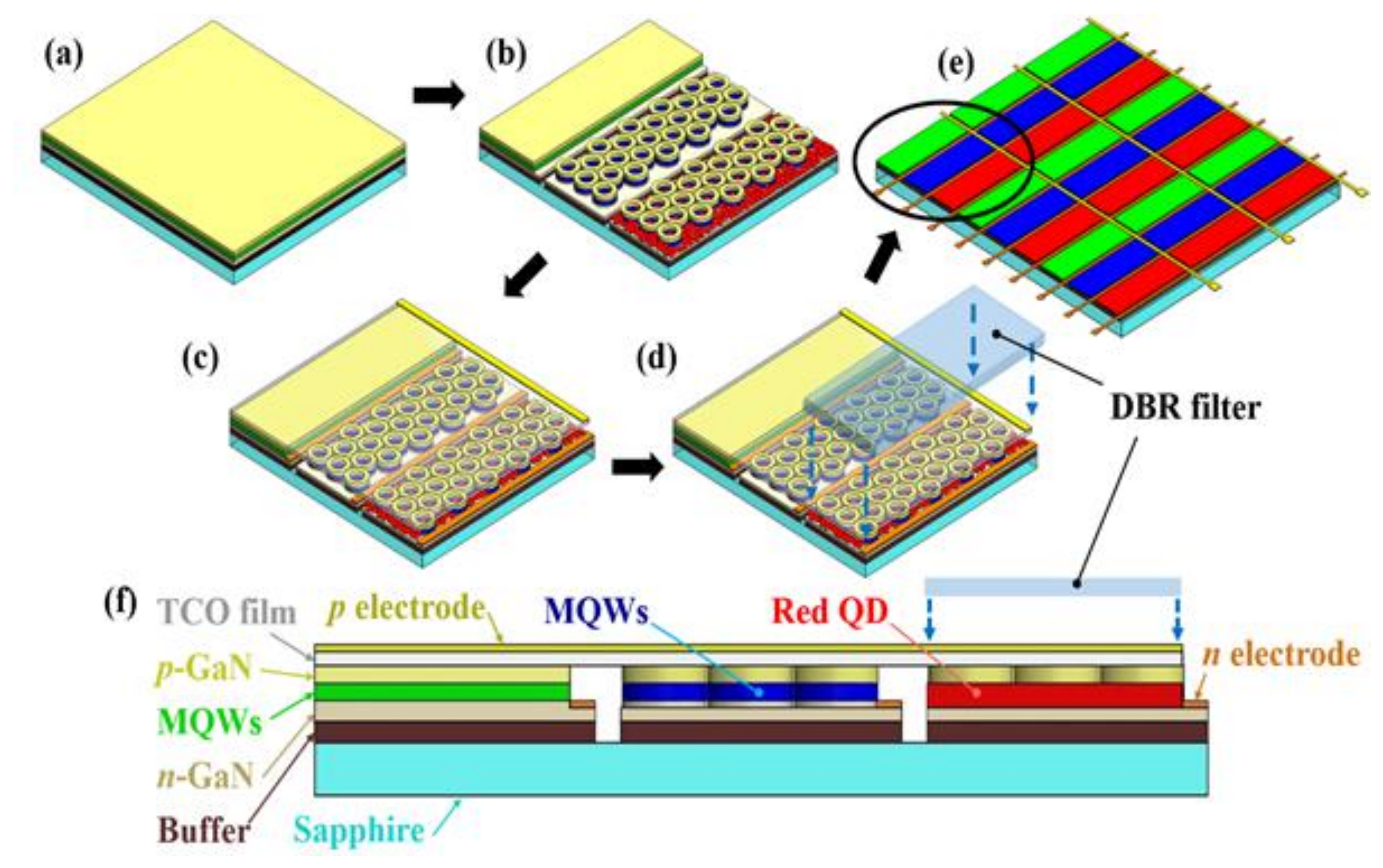

Figure 9: Manufacturing process of quantum dot nanoring micro-LEDs (image credit Picosun customer, Prof. Hao-Chung Kuo, NCTU Taiwan) [7]

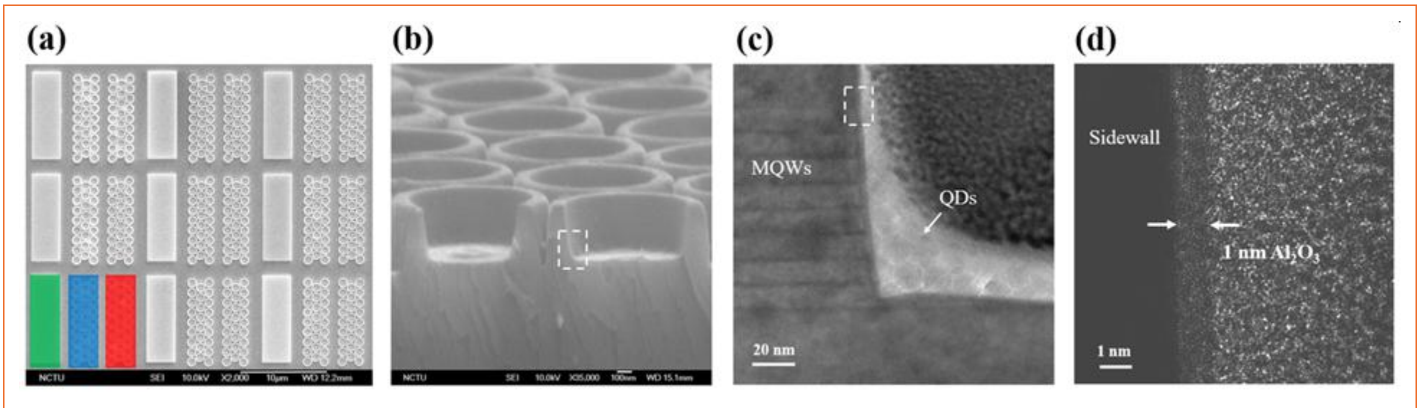

Figure 10: Quantum dot nanoring micro-LEDs: (a) SEM image of an RGB pixel array (top view); (b) SEM image of a nanoring micro-LED with 30° tilt angle; (c) TEM image of the contact area between multiple quantum wells and quantum dots; (d) TEM image of 1 nm Al_2O_3 deposited on the sidewall of a nanoring micro-LED with ALD (image credit Picosun customer, Prof. Hao-Chung Kuo, NCTU Taiwan) [7]

Sidewall Passivation and Light Confinement

Macroscopic, conventional LED chips are more or less "flat", but due to the shrinking dimensions, in micro-LEDs 3D geometrical aspects get highlighted. This means not only the phenomena occurring on the top of the LED matter, but those on the sides as well. Because of the minuscule dimensions and micropatterning, resulting in steep sidewalls, sharp angles and deep trenches with high aspect ratios, advanced surface treatment methods are called for.

Micro-LED manufacturing also utilizes flip-chip approach and chip-scale packaging, which makes sidewall protection even more important.

On all microscale devices, in general, surface passivation to eliminate traps and defects generated during the manufacturing process is needed when maximum performance and improved lifetime of the device are desired. In micro-LEDs especially, non-radiative recombination on sidewalls and subsequent loss of light intensity may be significant problem which must be solved.

A good passivation film must cover conformally all microscopic surface details and this is where traditional thin film deposition methods easily fail. ALD is able to form ultra-thin, conformal, uniform, reliable and pinhole-free passivation layer over the smallest nanoscale architectures of the micro-LED, while not interfering with the light output. Superior performance of ALD passivation, compared to PECVD, has been reported, where ALD resulted in lowest leakage currents and uniform light emission even for the smallest, only 20 µm × 20 µm micro-LEDs [5].

Another aspect related to the micro-LED sidewall, especially in chip-scale packaging, is light "leakage" through it. This can also be prevented with ALD by depositing thin reflecting layer, for example DBR stack made of alternating SiO_2/TiO_2 or Al_2O_3/TiO_2 films on the LED sides. This directs all light "out" from the top surface and improves notably the LED intensity.

ALD Passivation for Elimination of Manufacturing Damages

In micro-LEDs, especially novel architectures with sophisticated 3D details such as nanorings [6], surface damage caused by reactive ion etching may lead to notable decline of device performance. ALD surface passivation mends these damages, traps and defects, not only restoring the light intensity but boosting it to superior levels. At Picosun customer site, National Chiao Tung University (NCTU), Taiwan, light-emitting intensity of quantum dot nanoring micro-LEDs has been enhanced by 143.7% by using ALD passivation layers [7] (**Figure** 9, **Figure** 10).

ALD Applications for OLEDs

In OLEDs, the light-emitting layer is made of electrically active polymer materials. OLEDs generate soft and diffuse light over large area, they have excellent contrast ratio and bright colors, and they can be manufactured on lightweight, flexible substrates, but due to the organic core layer, their efficiency and lifetime are lower than those of other SSL devices. The organic, light-generating layer is extremely moisture-sensitive which is why hermetic encapsulation of the structure is essential for long operating life. ALD films' superior moisture barrier properties, as presented earlier in this article, make them a promising candidate to be utilized in OLED encapsulation. Ultra-thin, optically transparent ALD films are also well suitable for flexible substrates.

Naturally, other applications of ALD as presented in the previous chapters here are again valid for OLEDs as well: TCO layers, optical layers and passivation films. As ALD process temperatures are modest, and the method is gas-phased and gentle to the surface, it is very well suitable for plastic-based organic electronics such as OLEDs.

Summary and Conclusions

ALD is, by far, the most advanced and sophisticated thin film coating technology of today. Its key benefits over other methods – the films' superior conformality, uniformity, structural integrity and excellent barrier properties – combined with the modest process temperatures and surface-friendly film formation make it an ideal technique to manufacture functional and protective layers for LEDs. Especially for new technologies such as micro-LEDs, where manufacturers operate on micrometer or nanometer dimensions and totally new challenges emerge, ALD offers unrivaled possibilities to improve the device efficiency, light output, operational lifetime and reliability. ■

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ABOUT THE AUTHOR

Minna TOIVOLA, D.Sc.(Tech.): Dr. Minna Toivola has worked as the Marketing Manager of Picosun Group since 2010. In addition to Marketing Manager duties, she has also worked in Picosun's EU-projects, for example in the field of solar energy and corrosion protection with ALD. She has D.Sc.(Tech.) degree in Applied Physics, Renewable Energy Technologies from Aalto University (former Helsinki University of Technology), Finland, 2010, and M.Sc. in Physical Chemistry from University of Helsinki, Finland, 1998.

Optimized Light for Circadian Rhythm Synchronization Enhancing Indoor Lifestyles

Samsung Electronics

Spectrum engineering accurately realizes the functions of natural light, allowing users to maintain an optimal circadian rhythm. New developments discovered the melanopic spectrum that controls the melatonin hormone. The derived solution effectively manages melanopsin sensitivity at a wavelength of 480 nm, playing a critical role in circadian rhythm control for indoor lighting.

Introduction

We are spending most of our time indoors using artificial lighting. Melatonin, a hormone which regulates the sleep-wake cycle, responds to the cyan wavelength range of light. Brighter cyan-concentrated lighting suppresses the body's production of melatonin, increasing concentration and enabling a greater overall sense of alertness. Similarly, a lower cyan light intensity minimizes disturbances to the natural onset of the body's melatonin production, helping to promote sleep quality. Long exposure to bright light can confuse inbuilt natural circadian rhythms causing health problems such as insomnia.

Some studies, for example, showes that exposure to a spectrum with low power between 450–500 nm, but high power at even shorter wavelengths, did not suppress melatonin compared with dim light, despite a large difference in illuminance (175 lux vs. <5 lux). In contrast, exposure to the spectrum with high power between 450 and 500 nm (175 lux) resulted in almost 50% melatonin suppression [1].

Samsung's LM302N NITE

Samsung Electronics unveiled its first "human-centric" LED packages, collectively known as **LM302N**. Engineered with carefully created light spectra, the **LM302N** family helps human bodies adjust melatonin levels indoors, making people feel more energetic or relaxed depending on their daily life patterns.

"The benefits of using Samsung's LM302N reach beyond the basic lighting function of visual recognition, by improving the non-visual biological effects of lighting on people", said Un Soo Kim, Senior Vice President of LED Business Team at Samsung Electronics.

"Our LED solutions are ushering in a whole new human-oriented approach of using artificial lighting to enhance productivity and relaxation, benefitting modern-day indoor lifestyles," said Kim.

Samsung's **LM302N** utilizes precisely designed light spectra with optimized amounts of cyan to accommodate lighting needs to the extent desired at any given point in time: The **LM302N NITE** enhances relaxation. Standardized at 3.0×3.0 mm, these offerings can fit in a wide range of lighting fixtures and are protected against humidity and heat.

The **LM302N NITE** can provide a proper level of brightness without hindering the release of melatonin, helping people to maintain the hormone level as if they were in a calm natural atmosphere at night. The body releases about five percent more melatonin under lights with the **LM302N NITE** packages than conventional LED packages, increasing relaxation. By comparison, spending a lot of time under conventional nighttime lighting can cause excessive alertness that makes it harder to fall asleep. Additionally, the **LM302N NITE** is offered in color temperatures between 1800 K and 4000 K, providing design flexibility to bring the benefits of relaxing light to a variety of lighting spaces.

Clinical tests showed 18% more surpressed melatonin during the day, 5% more secreted melatonin at night, 3% more increased concentration, and 52 minutes earlier deep sleep compared with conventional LED lighting.

The newly launched **LM302N** family is now in mass production. ■

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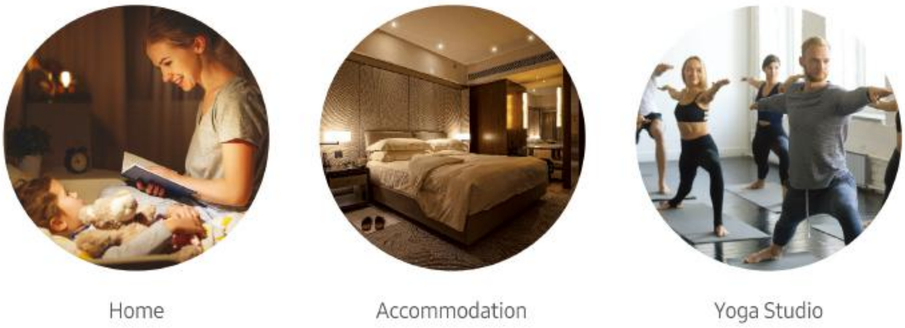
For more information:

https://www.samsung.com/led/lighting/mid-power-leds/3030-leds/lm302n-nite/



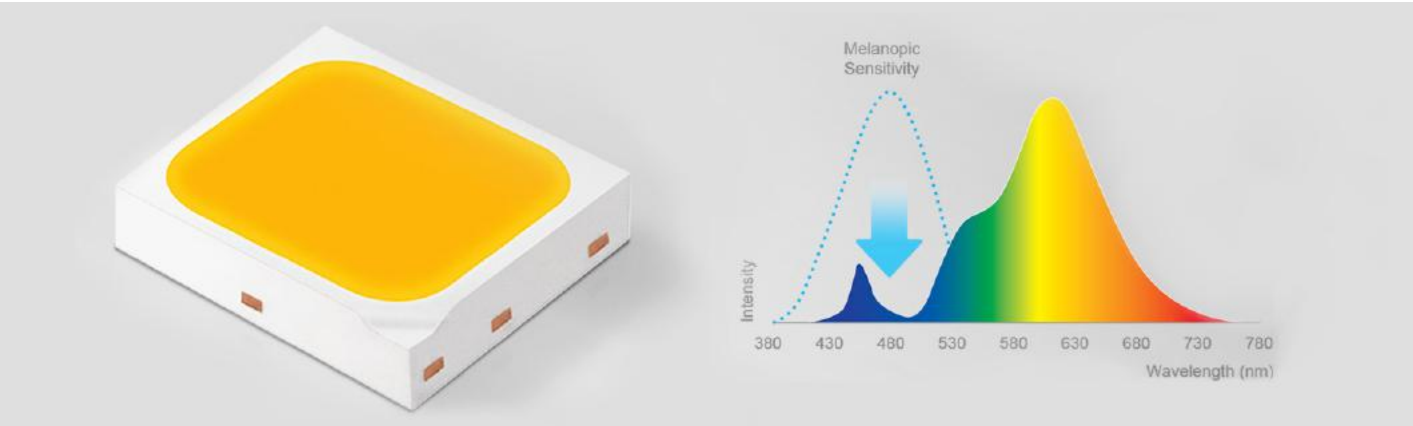


Figure 1: LM302N NITE – Lighting to relax: New LED packages help improve the quality of sleep by adjusting melatonin levels

CRI	CCT (K)	M/P Ratio*	MDER**	Size
80+	1800	0.20	0.18	3.0×3.0 mm
80+	2200	0.28	0.25	3.0×3.0 mm
80+	2700	0.37	0.34	3.0×3.0 mm
80+	3000	0.48	0.43	3.0×3.0 mm
80+	3500	0.56	0.51	3.0×3.0 mm
80+	4000	0.64	0.58	3.0×3.0 mm

Table 1: * M/P Ratio (Melanopic/photopic ratio): a measure of how efficiently a light source triggers suppression of melatonin. ** MDER (Melanopic daylight efficacy ratio): a measure of how bright standard light (Illuminant D65, defined by International Commission on Illumination) should be for a level of melatonin suppression comparable to the tested light source.

The Key Technology of Deep Ultraviolet (DUV) LEDs and Its Application

The global outbreak of COVID-19 has sparked interest in applying ultraviolet (UV) light for disinfection and sterilization. Academic circles have further explored its mechanism, functions and applications, and the industry has continuously rolled out new products to respond to the urgent need of fighting this pandemic. Stringent restrictions on the use of mercury in relevant international conventions highlight the advantages of deep ultraviolet (DUV/UVC) LEDs for energy conservation and environmental protections. DUV LEDs have many advantages, such as continuous and accurate wavelength adjustment, low voltage safety, easy to integrate and so on. It has broad applicable prospects in sterilization and disinfection, air and water purification, polymer curing, medical treatment, biochemical detection, gas sensing, and other fields. It is therefore an ideal option to replace the tradional UV light souce such as the mercury lamp. However, the luminous power, electro-optic conversion efficiency and lifetime of DUV LEDs are not as desirable and these challenges need to be addressed. The roles of traditional UV luminaries and DUV LEDs in sterilization and disinfection, the products' suitability for different scenarios, the efficacy and cost-effectiveness, irradiation dose and time parameters, limitations, etc., have been the concerns of those, inside and outside the industry. As per the requirements of ISA members, we have compiled the DUV LEDs Key Technology and Its Application in the Field of Sterilzation and Disinfection, which introduces the key technologies in the manufacturing chain of DUV LEDs, including MOCVD device technology, epitaxy technology, packaging technology, application areas, as well as respond to aforementioned concerns. This report aims to provide a "longitudinal profile" map of DUV LED from manufacture to applicatoin for those who are interested in this subject, to help people understand DUV LEDs more comprehensively, and to promote the safe, effective and wide applications of DUV LEDs in the world.

The Secretariat of International Solid State Lighting Alliance (ISA)
May, 2020

Introduction

With the continuous improvement of the quality of people's lives and the gradual implementation of the Minamata Convention that restricts traditional mercury-containing products, Deep Ultraviolet LEDs (DUV LEDs), as a new generation of high-efficiency ultraviolet light sources that are both energy-saving and environmentally friendly, have gradually become the mainstream of technology. AlGaN (aluminum gallium nitrogen) based ultraviolet LED has many advantages such as small size, mercury-free environmental protection, continuous and accurate wavelength adjustment, low-pressure safety, and easy integration. It has broad application prospects in sterilization, air and water purification, polymer curing, medical treatment, biochemical detection, gas sensing, special lighting and confidential communication, and is an ideal alternative to the traditional UV light source such as mercury lamp. With the rapid outbreak of new corona viruses in 2020, deep ultraviolet LEDs have the function of killing them, which has attracted extensive attention from technology and capital, and related products have been continuously introduced.

However, as the LED light emission wavelength becomes shorter, the difficulty of nitride UV LEDs from material growth to device preparation continues to increase, and the luminous power and efficiency gradually decrease. DUV LEDs are still in the early stages of product emergence, and their luminous power, electro-optical conversion efficiency, and lifespan are not satisfactory. …Further development also requires breakthroughs in the core technology of equipment, materials, devices, packaging, application, etc., practical and engineering to promote the deep ULTRA-VIOLET LED related products as soon as possible, to perfect and mature. In addition, the industry standards for DUV LED products have not been launched, which is a key factor affecting the development of the DUV LED industry.

This report describes the technology of deep ultraviolet LEDs in terms of metal organic chemical vapor deposition (MOCVD) equipment technology, epitaxial technology, packaging technology and application fields.

MOCVD Equipment Technology for Deep Ultraviolet

Background of High Temperature MOCVD Application Requirements

AlN-based wide bandgap nitride semiconductor materials have wide application potential in the field of leading-edge optoelectronics and microelectronics devices. UV LEDs based on AlGaN materials with high aluminum composition have shown huge market application prospects in many applications, which has been initially applied at present. The method commonly used for the preparation of high-aluminum nitride deep UV LED materials is MOCVD technology, which controls the growth of the epitaxial layer by controlling the flow rate of the gaseous reaction source and the temperature and pressure of the reaction chamber, which is suitable for the growth and preparation of compound semiconductor materials. It has the advantages of high flexibility, high uniformity, excellent uniformity and repeatability, and is currently the most mainstream key equipment for the research and production of compound semiconductor epitaxial materials. One of the main features of AlN-based nitride semiconductor materials is the high growth temperature. Therefore, high-temperature MOCVD equipment is used to prepare high-aluminum nitride DUV LED materials. With the continuous expansion of the high-aluminum component materials device market, the demand for high temperature MOCVD is also growing.

Current status and technical challenges of high-temperature MOCVD

High-temperature MOCVD technology has been developed as the research and applications of high-aluminum content AlGaN deep ultraviolet LED developed in the past decades. Currently the GaN- or GaAs-based MOCVD equipment has been commercially available, but there are no commercial high-temperature MOCVD equipment specially for research and development, and industrial applications due to the difficulties in epitaxy of AlN-based materials. The high-temperature MOCVD equipment produced by the world major MOCVD manufactures is transformed from the GaN-based MOCVD equipment. But this kind of production still remains several issues like low productivity and instability. Some institutions have started to develop the high-temperature MOCVD equipment, yet the innovation still lies at the stage of improving the quality of AlN-based materials. As the market expands, high-temperature MOCVD equipment will serves as a new growing point of market. Hence, the world major manufactures and institutions are dedicated to develop this equipment by continuously investing the R&D efforts. It can be expected that the commercialized exclusive high-temperature MOCVD equipment will be gradually applied in the medium and top industrial markets like DUV.

The whole structure of high-temperature MOCVD equipment, similar as that of the conventional MOCVD, is composed of reaction system, extraction system of exhaust gas, heating and spinning system, gas transportation system, electrical power distribution system, and automatic control system. The characteristic of high-temperature MOCVD depends on that of epitaxy of high aluminum content nitride. When AlN or other high Aluminum content materials grow in MOCVD, it has special and higher requirements for equipment's temperature, pressure, and flux and thus is more sensitive to the equipment's heat control, flux control, and pressure control than that by the conventional MOCVD. Hence, high-temperature UV MOCVD is facing several technical challenges and difficulties which will be described below.

Large size high temperature heating system with homogeneity and stability

Owing to relatively larger chemical bond energies (2.88 eV) between Al and N, the mobility of Al atoms on the growing surface is poor, which results in 3D island growth in the vapor deposition epitaxy. The higher the Al content of AlGaN material, the severer the 3D island growth. Thus, it requires high growth temperature for growing AlN-based materials, sometimes even more than 1500□. Al atoms have higher and better surface migration performance at high growth temperature, which help obtain high quality epitaxy materials. The requirement of higher temperature leads to different and novel designs of epitaxy equipment in heating manner, temperature control, and cooling process. Hence, the development of large size high temperature heating system with homogenity and stablity is the key in developing high temperature MOCVD.

Reduction of pre-reaction in the reaction chamber

The pre-reaction easily occurs between the active organic precursor of Al used in growing high aluminum nitride and NH_3

gas in the vapor deposition process, which all happens in vapor phase. The nano- to micro-size complex compound powders formed during high-temperature combination and decomposition of pre-reaction not only reduce the incorporation ratio of Al precursor and decrease the AlN growth efficiency, but also adversely affect the materials' crystal quality and surface morphology by depositing on the material surface in the growth process. The factors like distribution of reactants, temperature gradient in the reactor chamber, and flow velocity are being taken into account when considering how to reduce or eliminate the pre-reaction in the growth process. The elimination of pre-reaction by special design of flow and temperature distribution is also a key technical obstacle to be solved in high-temperature MOCVD growth chamber.

The special epitaxy technique corresponding to high-temperature MOCVD

In the process of epitaxy growth of high Aluminum content AlGaN materials by high temperature MOCVD, the technical difficulties lie in improving material quality, increasing growth rate, and eliminating cracks on the epitaxial layer caused by high-temperature thermal stress. As the Aluminum content increases, it is getting harder and harder to improve the crystal quality because of higher dislocation density, slower growth rate, and lacking of the quality of impurity incorporation. Moreover, larger lattice mismatches between hetero-epitaxy substrate and high aluminum content nitride epitaxial materials and thermal expansion coefficient difference when the temperature difference between rise-up and cool-down exceeds 1000 °C usually lead to film crack formation and failure of film application by accumulating stress of epitaxial layer. Hence, developing special epitaxy technique corresponding to high-temperature MOCVD is one of the major difficulties and challenges in improving high-temperature MOCVD technology.

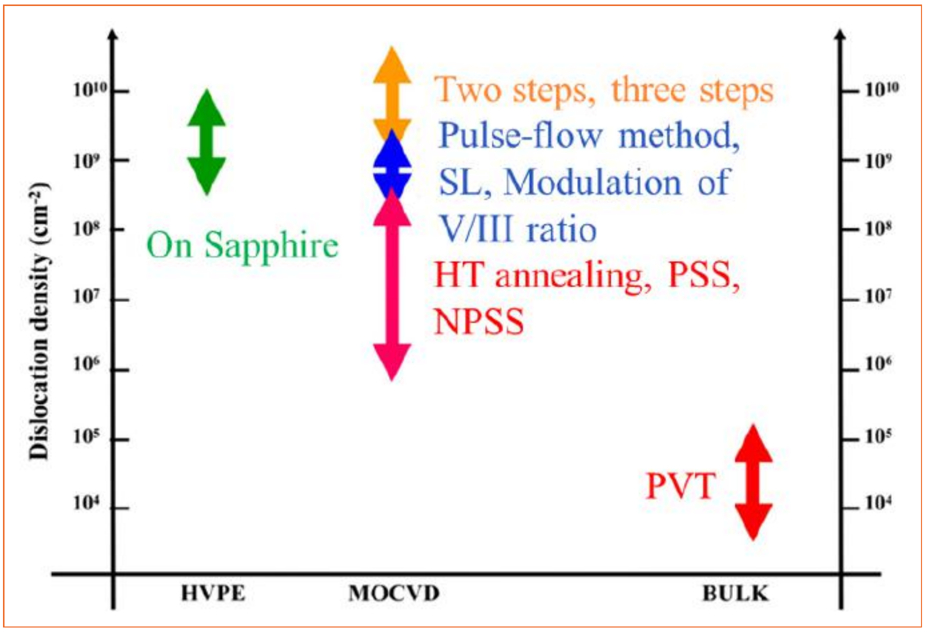


Figure 1: Various methods to fabricate AlN template

DUV LED Epitaxy and Chip Technology

AlN Substrate

Homoepitaxy is epitaxial growth on the substrate with the same material. It is considered the most perfect epitxial growth because of lattice match and themal match. For DUV LED, it is easy to grow high-quality AlGaN film on AlN substrate and the quality of AlGaN film mainly depends on the quality of substrate material. Therefore, AlN substrate with low dislocation density is very important for high-performance DUV LED. To fabricate AlN substrate, there are two ways, HVPE and PVT.

AlN single crystal growth by HVPE is to grow thick AlN film on sapphire with high growth rate. In this process, the dislocation density caused by lattice mismatch will reduce to the level of 1E6 cm^{-2} due to dislocation annihilation. However, due to the decreasing dislocation density, dislocation encounter and recombination become difficult. Therefore, it is very difficult to reduce dislocation density of AlN with HVPE growing method. The good thing is that the size of AlN grown by HVPE is decided by the size of substrate, which means it is easy to get large-size AlN substrate. Another advantage of HVPE growth is that there is low impurity density in AlN film, which has high transmittance for DUV emission.

The theory of AlN growth by PVT is that AlN powder is sublimated at higher temperature and decomposed into Al gas and N_2. Then these two gases transport to lower temperature zone and react and deposit on the substrate. PVT can get AlN bulk with low dislocation density. PVT growth has two ways, spontaneous nucleation and seed growth. Spontaneous nucleation can get AlN with low dislocation density, however, the size of AlN is very small. On the other hand, seed growth can achieve large-size AlN bulk with high dislocation density if use foreign substrate like HVPE. Therefore, seed growth on AlN substrate by spontaneous nucleation is the best method for AlN PVT growth. Recently, American and German group have already fabricated 2-inch AlN substrate by using this method. The dislocation density is below 1E4 cm^{-2}. However, AlN bulk by PVT is dark red, which means that it has high impurity density. It is mainly because the AlN power has many impurities and carbon impurities are easily volatilized from caron felt at high temperatures. This high impurity density will strongly absorb DUV emission. It is necessary to decrease the impurity density so that AlN substrate can be applied for DUV LED in the near future.

AlN Epitaxial Growth on Large Lattice Mismatch Substrate

Due to hard fabrication and high cost of AlN substrate, sapphire substrate is widely applicated for DUV LEDs because of low cost and high transmission of DUV emission. However, because of the large lattice mismatch and thermal mismatch between AlN and sapphire and the low migration of Al on the surface, AlN grown on sapphire will crack easily and has high threading dislocation density.

At present, there are some ways to reduce the threading dislocation density and strain of AlN films, such as two-step growth, three-step growth, pulse growth, nano-pattern sapphire substrate (NPSS). Among them, NPSS can relieve strain and reduce TDD to 1E8 cm^{-2} and improve the light extraction efficiency. However, the fabrication of NPSS is so complicated that the cost become higher. As a whole, because the growth temperature for high-quality AlN is very high, MOCVD needs special materials and design for the reactor. Moreover, the higher the temperature, the more difficult to control the thermal uniformity of the reaction chamber. Therefore, the reactor for growing DUV LEDs is usually small, which means less pieces at once. Recently, researchers exploit another method to fabricate AlN/sapphire template, named as high temperature annealing. First, low-quality AlN/sapphire templates are fabricated by MOCVD or sputter. And then these low-quality AlN/sapphire templates are put into high-temperature equipment face to face and annealed at high temperature for several hours to improve the quality of AlN film. The TDD of AlN will reduce to 1E8 cm^{-2} by this method. The process is simple and stable, and it is a better process route for preparing AlN template.

AlGaN Epitaxial Growth

Due to the large strain caused by the lattice mismatch between AlGaN and AlN, AlGaN grown on AlN easily has relaxion when Al content of AlGaN is below 0.7 and many dislocations appear to relieve stress at the same time. To solve this problem, some researchers directly grow thick AlGaN films on AlN to get high-quality AlGaN films. In this process, some dislocations caused by relaxion meet with each other and annihilate, therefore, TDD become lower. Besides, some researchers insert AlGaN/AlN superlattice layer or graded AlGaN layer between AlGaN and AlN to control the strain. In this way, n-AlGaN is always at the state of strain without new dislocations and TDD is decided by AlN template.

During high-quality AlGaN growth, GaN easily decompose because of high growth temperature and Ga vacancy always appears. This Ga vacancy compensates the donor Si which causes to decrease electron concentration of n-AlGaN film. On the other hand, activity energy of electron in AlGaN is larger because of large bandgap of AlGaN. Moreover, Si doping density will become low with increasing growth temperature. Therefore, electron concentration of n-AlGaN film is lower than n-GaN which causes the increasing of the voltage of DUV LEDs. Thus, it needs further improvements.

P-type Doping of Al-rich AlGaN Material

The n-type and p-type doping efficiencies of Al-rich AlGaN materials are relatively low, compared with that of GaN materials. Because as the Al composition increases, the bandgap of the AlGaN material increases, and the donor and acceptor energy levels become deeper. The activation energy of the donor and the acceptor continues to increase, resulting in a reduction in the carrier concentration and finally a reduction in the carrier injection efficiency and the internal quantum efficiency. The p-type doping issue is more prominent. The hole concentration in p-type AlGaN materials can be given by the following formula:

$$p = N_\nu^{\left(-\frac{E_F - E_\nu}{kT}\right)} = N_\nu^{\left(-\frac{E_A}{kT}\right)} \qquad (1)$$

Where E_F and E_A are the Fermi level and the valance band, respectively, E_A is the activation energy of the acceptor, N_ν is the effective state density near the top of the valence band, k is the Boltzmann constant, and T is the thermodynamic temperature. At room temperature, the activation energy E_A of the Mg acceptor increases almost linearly from 160–200 meV in GaN to 510–630 meV in AlN, implying that the activation efficiency of the Mg acceptor in AlN is less than 10^{-5} of that in GaN, and the hole concentration in AlN is extremely low. In order to achieve a higher hole concentration, it is a common practice to increase the Mg dopant concentration to reduce E_F. But an excessively high dopant concentration tends to deteriorate the crystal quality of AlGaN materials and raise the density of structural defects (such as vacancies and Mg-N composites, reverse phase domain boundaries and stacking faults). Consequently, the carrier compensation effect intensifies, the carrier mobility decreases, and the conductivity of the doped AlGaN layer reduces, which imposes an adverse influence on the electrical injection efficiency and luminous efficiency of the LED. Some studies also show that the Mg acceptor itself and the defects generated when Mg impurities are incorporated will bring absorption loss to the light radiating from the active region.

To improve the p-type doping efficiency and increase the hole concentration of Al-rich AlGaN materials, several approaches have been reported:

- p^+-GaN/p-AlGaN heterojunction. A p^+-GaN layer grows on the Al-rich p-AlGaN layer; two-dimensional hole gas (on the order of 1013 cm^{-2} or higher) accumulates in the p-GaN layer near the heterojunction interface due to the polarization charge at the interface induced by the piezoelectric polarization and the spontaneous polarization. Holes can be then injected into p-AlGaN layer and the active region via the thermal emission and the tunneling. Thus, the conductivity of p-AlGaN layer and the carrier injection efficiency are imporved. This method is commonly applied in DUV LEDs. However, the p-GaN layer will strongly absorb the light radiated from the active region because of its narrow bandgap. Researchers have proposed a thin p-GaN contact layer or a patterned p-GaN contact layer to reduce the light absorption loss.
- Al(Ga)N/GaN short-period superlattices. This method takes advantage of the polarization effect and the periodic oscillation of the valence bands in the superlattices, and prompts the acceptors where the valence band is close to or above the Fermi level to be ionized to provide holes. But the superlattices will inevitably introduce multiple barriers in the vertical direction. To alleviate this problem, the short-period superlattices doping technique can be adopted in combination with the acceptor delta-doping, Mg-Si co-doping or other technologies. Recently, researchers from Xiamen University reported to use three-dimensional Mg-doped superlattices to increase the vertical conductivity.
- Polarization induced doping via grading the Al composition. The polarization field at each unit cell interface encounters abrupt change when the Al composition of the AlGaN layer is gradually changed, which induces a uniformly distributed net polarized negative bound charge in the p-AlGaN layer. To maintain the electric neutrality, three-dimensional hole gas is induced, and the hole concentration is determined by the composition gradient of Al. The negative bound charge can also generate a high polarized electric field, which promotes the ionization of the Mg acceptor. Since Mg atoms are mainly ionized by the electric field, the hole concentration is nearly independent of the temperature. What's more, the valence band of the p-AlGaN layer is smooth, which will greatly benefit the holes' vertical transport. This technique has been successfully applied to the structure of DUV laser diodes, and the electrical injection lasing has been achieved.
- Tunnel junction composing of p-AlGaN/a thin insertion layer (IL) with narrow bandgap and low resistance/n^+-AlGaN. Strong net polarized charge is induced near the interfaces between AlGaN layers and the IL, which generates a high polarization electric field in the thin IL. The energy band of the IL inclines sharply within such a small length that the valence band of p-AlGaN and the conduction band of the n^+-AlGaN are aligned in a range of a few nanometers. Therefore, the height of the tunneling barrier is effectively reduced. To further reduce the width of the depletion barrier and increase the probability of tunneling between bands, AlGaN layers with graded

composition are proposed to be grown on the both sides of the thin IL. When the DUV LED is forward driven, the tunneling junction is reverse biased. The electrons in the valence band of p-AlGaN tunnel into the conduction band of the n^+-AlGaN, and nonequilibrium holes are generated and injected into the p-AlGaN layer. However, the turn-on voltage of the DUV LED devices using the tunnel junction is increased significantly. Therefore, more optimization studies are needed.

Polarization effect

The metal-polar AlGaN material has a strong instinct spontaneous polarization effect. The spontaneous polarization direction is along the (0001(-)) direction (that is, along the direction of the substrate). As the Al composition increases, the spontaneous polarization increases. In addition, the AlGaN quantum barriers and wells in UV LEDs have different compositions. The quantum wells are in compressive stress, leading to the piezoelectric polarization effect. The piezoelectric polarization direction is along the (0001) direction. The directions of spontaneous polarization and piezoelectric polarization in the quantum wells are opposite, but the spontaneous polarization in the quantum barriers is stronger than the spontaneous polarization in the quantum wells. Net polarized surface charge will eventually be generated at the barrier/well interfaces. The net polarized surface charge introduces a strong polarized electric field in the quantum well region, causing the band bending and spatially separating the electron and hole wave functions. That is the so-called quantum confined stark effect (QCSE). The QCSE will increase the carrier lifetime, and reduce the radiative recombination probability and the internal quantum efficiency. A redshift of the emission wavelength will emerge when using wide quantum wells. Narrow quantum wells can help to alleviate the QCSE.

The polarization effect will also cause the energy band bending downward at the interface of the electron blocking layer and the last quantum barrier, leading to the carrier leakage phenomenon. Optimizing the design of the energy band structure to regulate or eliminate the polarization electric field inside the LED is an important research aspect to improve the LED quantum efficiency.

Research on the epitaxy and fabrication of UV LEDs on semi-polar and non-polar substrates is also gradually emerging. Although the polarization effect still exists in the semi-polar and non-polar quantum wells, its direction has a certain angle with the growth direction. The QCSE in the quantum wells is weakened or even completely eliminated, and thus has little effect on the shape of the energy bands.

Light extraction of DUV LEDs

The poor light extraction efficiency (LEE) is one challenge in obtaining highly efficient AlGaN-based DUV LEDs. As mentioned above, UV LEDs generally employ a p-GaN/p-AlGaN heterojunction to enhance the hole injection efficiency and improve p-type ohmic contact. But the p-GaN layer has a narrow bandgap with a band edge wavelength at about 365 nm. The upward UV light radiating from the active region is strongly absorbed by the p-GaN layer. This is why UV LEDs usually adopt a flip-chip configuration. Developing a transparent p-type AlGaN structure layer with sufficient doping efficiency and simultaneously combing with highly reflective p-type metal electrodes can effectively reduce the light absorption loss. Part of the emitted light can be reflected back to the substrate side and the probability of light escaping through the substrate is improved.

Secondly, serious total internal reflection (TIR) occurs at the semiconductor layer/substrate interface and the sapphire substrate/ambient interface due to the large refractive index difference (nAlGaN $\approx$ 2.1 – 2.6, nsapphire $\approx$ 1.8, nair = 1). According to the Snell's law, the critical angle of TIR on the interface of sapphire substrate to air is only about 33° at a wavelength of 275 nm. Most of the light emitted from the quantum wells is confined inside the epitaxial layers and the substrate as optical waveguide, and eventually converted into thermal heat after the reduplicative oscillation and the continuous absorption. Surface pattering is one promising approach to reduce the TIR of light and improve the LEE. For example, fabricate a microlen array or a moth-eye structure on the backside of sapphire substrates, induce a roughened layer structure by laser stealth dicing on the sidewalls of the substrates, or construct air voids in the micro/nanometer scale inside the chip via the epitaxy process.

Utilizing the forbidden bandgap effect or the grating scattering effect of the photonic crystal can also improve the LEE of UV LEDs. The former effect requires the photonic forbidden bandgap to cover the spectral range of the emission from the active region, implying that the period of the photonic crystal needs to be reduced below the wavelength. For AlGaN-based DUV LEDs, the period should be less than 100 nm, which requires tough technology; and the photonic crystal needs to be set very close to the quantum well region. Actually, it is difficult to prepare such a photonic crystal structure to DUV LEDs in practice. For the latter effect, the photonic crystal structure is generally prepared on the LED surface, which can compensate the lateral wave vector of the waveguide mode at the interface and help extract the waveguide mode light. Researchers from Japan reported that fabricating a composite nanostructure composing of a two-dimensional photonic crystal and a sub-wavelength nanostructure on the back surface of the AlN homogeneous substrate increased the optical output power of 265 nm LED by 196%. The optical output power at 350 mA reached up to 90 mW.

Besides, the intrinsic anisotropic optical polarization properties of Al-rich AlGaN materials also affect the LEE dramatically. Light emits from c-plane AlGaN-MQWs as either transverse-electric (TE) mode with electrical field vector E perpendicular to c-axis or transverse-magnetic (TM) mode with E parallel to c-axis. And the TM-mode light comes to predominate over the TE-mode light when the emission wavelength gets shorter than 300 nm. As is known, the TE-mode light mainly propagates in the vertical direction; while the TM-mode mainly transmits in the horizontal direction, which is difficult to extract due to larger incident angle on the surface. Ryu et al.'s simulation showed that the TM-mode LEE is much lower than the TE-mode LEE, which is partly responsible for the decrease of LEE in DUV LEDs with shorter wavelength.

To address this issue of the low LEE of the TM-mode light, there are mainly two methods. One is using a reflector or scattering structure or nano-pillar structure to modulate the light propagation direction inside the LED structure. The propagation direction of the TM-mode light is altered to the substrate side, and the LEE is improved. The other one is adjusting the order of the valence sub-bands at the □ point in the Al-rich quantum wells using narrow compressive quantum wells or energy band engineering, and thereby enhancing the intensity of the TE-polarized light relative to the TM-polarized light emitted at a certain wavelength. The dominant light emission mode is converted from the TM-mode to the TE-mode which is easier to be extracted. This method is expected to solve the problem of optical extraction from anisotropy of TM modes.

Deep-Ultraviolet Light Emitting Diode Packaging Technologies

Currently, the efficiency of most deep ultraviolet light emitting diodes (DUV LEDs), that have a wavelength of less than 300 nm, is still very low. External quantum efficiency (EQE) of most reported DUV LEDs is below 6%. As the internal quantum efficiency (IQE) continues rising, one of the most important reasons for the poor EQE is the low light extraction efficiency, brought by limitation of DUV LED packaging technology. Due to the character of DUV LEDs, the structures and the materials of DUV LEDs are different from the visible LEDs, adding difficulties to related research.

Compared with the visible LEDs, the difficulty of DUV LED packaging is mainly reflected in the following two aspects. One is that most visible LED packaging materials are not compatible with UV bands. Most of the organic materials used in the traditional visible LED packaging can strongly absorb UV light. Especially for DUV LED, the transmittance of common packaging organic materials below 300 nm decreases sharply with the decrease of wavelength, and it is prone to deterioration and yellowing under long-term UV light irradiation, resulting in loss of transparency and LED photo-attenuation failure. On the other hand, the self-heating phenomenon of DUV LEDs is more than serious, and the power of heat dissipated is about 98% of the total in the case of DUV LED packaging. The rise of junction temperature caused by the self-heating not only greatly changes the optical characteristics of LEDs, but also reduces the life of the chips and the packaging materials. Besides, since p-GaN layers of DUV LEDs show strong absorption in the DUV region, little DUV light can pass through the p-GaN layer. Thus, DUV LED packaging is dominated by flip-chip structures, with a few vertical structures.

Due to the above factors, it is difficult for DUV LEDs to use the traditional organic packaging of visible LEDs directly. All-inorganic packaging is a developing direction of DUV LED packaging that has received widespread attention. Firstly, a flip-chip DUV LED chip is bonded on a ceramic substrate using inorganic solder or eutectic welding. Then, a quartz lens is bonded on the dam of the ceramic substrate by inorganic welding in a vacuum environment or a nitrogen atmosphere to obtain hermetic packaging. Compared with organic packaging, in this structure, the organic encapsulant is replaced by airtight protection, and the organic lens is replaced by a quartz lens (sometimes the sapphire lens is also used). No organic materials are used in the entire packaging process, while the used inorganic materials have good UV resistance and thermal conductivity. Thus, the packaged DUV LED device will have better reliability. The most difficult process of all-inorganic packaging is the quartz lens bonding. The bonding process can be divided into two types: integral heating and local heating. It is easy to bond the quartz lens by soldering through the integral heating. However, the high temperature of the integral heating is easy to cause thermal damage to the chip and its bonding layer, reducing the reliability of the chip. Therefore, the way to bond the quartz lens by local heating has attracted wide attention, while various methods have been developed, such as induction heating and laser heating. However, these methods also have problems, such as difficulty to control and high cost. Therefore, it is still difficult to apply the local heating to commercial DUV LED all-inorganic packaging on a large scale.

Therefore, at present, the most common commercial DUV LED packaging chooses to introduce some organic materials in some non-critical positions based on all-inorganic packaging to reduce packaging difficulty and reduce costs. For example, the quartz lens of commercial DUV LED packaging is always pasted by organic adhesive. Compared with all-inorganic packaging, due to the aging and deterioration of the organic adhesive under DUV light, this structure must show low bonding firmness and poor airtightness. Therefore, some commercial designs tried to place the organic adhesive outside the light path of the LED, thereby reducing the influence introduced by using organic adhesives. For example, a groove is made on the metal dam and the organic adhesive is coated into the groove to reduce the possibility of DUV light irradiating, and increase its life span.

Unlike the inorganic bonding process of quartz lenses, the hermetic packaging technology using vacuum or nitrogen has been widely used in commercial DUV LED packaging. However, due to the huge refractive index difference between the sapphire substrate of the flip-chip DUV LED and vacuum or nitrogen, very severe total reflection and Fresnel reflection are introduced at this interface by using hermetic packaging. Besides, without the underfill by the encapsulant, serious heat accumulation can be introduced in the gap between the bonding layer of the flip-chip LED and the substrate, making the heat dissipation problem of the DUV LED more serious.

Therefore, although few commercial DUV LEDs using organic encapsulants, the research about the encapsulants compatible with DUV LED packaging has not stopped. UV Craftory Co., used the fluororesin in DUV LED organic packaging, and conducted a lot of research on this kind of material to confirm its feasibility. Researchers from Taiwan used silicone oil for DUV LED liquid packaging, which also showed exciting results. In addition, there are other Chinese and foreign researchers trying to synthesize some new materials with UV resistance. However, these studies still have a distance from commercialization due to limitations introduced by cost and process.

Research on packaging substrates used in DUV LED packaging has also attracted wide interest. Due to the heat dissipation requirement of DUV LEDs, ceramic substrates have become the mainstream of DUV LED packaging substrates. There is no organic material inside the ceramic substrate. Therefore, thermal conductivity of a ceramic substrate is almost equal to that of the bare ceramic, which can provide a strong heat dissipation capability. Now, the most commonly used ceramic substrate is direct plated copper (DPC) ceramic substrate. The circuit pattern of the DPC ceramic substrate is obtained by photolithography process. Then, the Cu circuit is obtained by electroplating or chemical plating. The DPC ceramic substrate has the semiconductor compatible process, good reliability, high thermal conductivity, and high graphic accuracy. Thus, it is very suitable for flip-chip LED packaging.

The DPC process can also be used to obtain a 3D substrate with a metal dam based on a planar ceramic substrate, which avoids the difficulty and the risk of falling off when bonding an independent dam on the planar substrate. Besides, dams prepared by inorganic slurry on the planar DPC ceramic substrate have also received attention. This kind of dam has not only a very high reflectivity in the DUV region but also a low cost. A metal coating film is usually plated on the Cu circuits of DPC ceramic substrates to prevent oxidation of Cu circuits and improve solderability. Ni/Au coating film is usually used as a coating film of DPC ceramic substrates for DUV LED packaging. However, Au has strong absorption in the DUV region, which reduces the efficiency of DUV LEDs.

Therefore, some Al metal substrates were used in commercial DUV LED packaging instead of DPC ceramic substrate. Al metal substrates have an easier process and lower cost, and due to the low absorption of Al in the DUV region, DUV LEDs packaged by such substrates can show higher efficiency in the short term. However, there is an organic insulating layer inside the Al metal substrate, which is not a completely inorganic structure. The organic layer not only brings poor heat-dissipation capacity, but also is easily deteriorated under the DUV irradiation and severe thermal effects, which introduce a shorter lifetime. Due to the aforementioned disadvantages, the Al metal substrate cannot replace the DPC ceramic substrate in DUV LED packaging.

In summary, the current mainstream commercial DUV LED packaging structure is a structure close to all-inorganic packaging. A lip-chip DUV LED is soldered on a DPC ceramic substrate with a metal dam, and then a quartz lens is pasted onto the dam by organic adhesive to obtain a vacuum or nitrogen hermetic packaging. This structure considers the balance between device cost, efficiency, and reliability. But there are still problems and defects, such as severe reflection, unreliability of organic adhesives, and severe thermal effects.

Based on this structure, research on many other aspects of DUV LED packaging is also in progress. In the future, research on all-inorganic encapsulated DUV LEDs and new organic materials suitable for the DUV region, especially organic packaging using fluororesin, which have obtained some results, will still be hot spots. Future research will focus on simplifying their processes and reducing their costs. All-inorganic packaging pays more attention to the reliability of DUV LEDs, while organic packaging can improve the efficiency of DUV LEDs while ensuring acceptable reliability. Now, the organic packaging cannot be used in DUV LED packaging mainly due to restrictions on organic materials. Once reachers make a breakthrough in materials, the organic packaging still has advantages in general applications.

Therefore, looking for batter organic materials with sufficient transparency and stability in the DUV region will be a long-term goal in DUV LED packaging. Besides, as the packaging technology matures, research about DUV LED packaging will be more comprehensive, and the exploration of new structures and new processes will also be paid more attention. For example, high DUV reflective inorganic dams with low cost and high efficiency, new substrates that combine the reliability advantages of DPC ceramic substrates and the efficiency advantages of Al metal substrates, new lens structures for adjusting light distribution, and so on.

The Application Field of Deep UV

In the face of the epidemic, the term “sterilization” has taken root in peoples’ hearts. Many methods of sterilization have been accepted by the public, whether with alcohol, 84 disinfectant or deep ultraviolet. At this time, the higher technology of deep ultraviolet sterilization received more attention, deep ultraviolet sterilization has been widely used in many fields. For example, it can be used to sterilize water, air and surfaces. Therefore, it can be widely used in the field of water purification, air purification, medical treatment and other fields. Deep ultraviolet sterilization is divided into mercury lamp and UVC LED two camps. It can be used as a light source for most sterilization applications, because of the compact and portable LED and its large light density.

There are three main drivers for the growth of the UVC LED application market: surface/air sterilization, static water sterilization and water sterilization. It requires a shorter exposure time in static water and surface disinfection (for air purification and appliances, etc.). They are also driving many emerging markets, including baby products, mobile phones, escalators, household products (such as toothbrushes), toiletries, cupboards, sports kettles and thermos.

Because of its rapid action of the characteristics of the more demanding, water sterilization needs higher power. It will be used in the domestic water treatment market includes water dispensers, hot and cold kitchen water, whole-house water purifiers and baby products (baby formula).

From a commercial and industrial perspective, the global water treatment market is about USD 20 billion, making it the target market for UVC LEDs with the greatest potential for growth. The three main methods used in water sterilization are gravity-based purification, RO purification and UV purification. RO purification is a widely used technology, but it still should be used in combination with UV purification to remove bacteria and viruses from water.

In order to meet the demand of the water treatment market, Japanese and Korean manufacturers are actively developing high-power UVC LED and entering the water module market. LEDinside predicts that the UVC LED market will be divided into two parts: the general consumer market and the advanced commercial/industrial market. From the data of household UVC products on various network platforms, the sales volume of mercury lamp products is far higher than that of UVC LED products. Mercury lamp products are mostly used for overall sterilization of room space, while UVC LED products are widely used for household products and travel sterilization. With the gradual improvement of research and development capacity, the technology of deep ultraviolet LED becomes more and more mature, and the application range of UVC LED sterilization products will become larger and larger. At present, the mainstream household UVC LED sterilization equipment, including sterilization box, sterilization bag, sterilization stick, toothbrush sterilizer, kitchen sterilizer, contact lens sterilizer, mobile phone sterilizer and so on. From the perspective of sales volume, the sterilizing rod and sterilizing bag with wide range of functions are more popular, while the toothbrush sterilizing device with considerable sales volume is closely related to its convenience. Besides, it is a product that is used many times a day, and it is very convenient to operate.

From the sales volume of UVC sterilizing products on Taobao platform, the sales volume increased sharply from February to March in 2020 and reached the peak. Since April, the epidemic in China has been successfully suppressed, and the demand for sterilizing products has decreased significantly. However, the international market is still hot.

According to a report released by Trend Force LED research center (LEDinside), UVLED products are actively used in various applications, and UVLED is expected to reach USD 1.124 billion by 2022, with the Minamata Convention banning the production and export of mercury-containing products by contracting states by 2020. The compound annual growth rate of the UVLED market is 33%. Among them, the growth of UVA LED is about 10%, UVB LED is 11%, and UVC LED is relatively high, reaching about 74%. In terms of market share, UVC LED will account for 73% of the market by 2022. Looking forward to the application market demand, surface/air sterilization and purification, still water sterilization and flowing water sterilization are the main growth drivers in the future. It is estimated that the output value of UVC LED products will reach USD 991 million in 2023.

The main factors driving the growth of the market are the emergence of new technologies on a global scale, the increasing promotion of energy-saving government policies and the increasing application of UVC LED technology. UVC LED products are expected to dominate the market during the forecast period due to the increased adoption rate of advanced disinfection and purification systems.

The market of UVC chip and lamp bead is currently at the critical point of the market, many manufacturers are actively layout. Japanese and South Korean manufacturers are the pioneers, Chinese manufacturers are late in transition, only some manufacturers of China can achieve trial production and mass production. Japanese and South Korean manufacturers are more active in the UVC chip and lamp bead market, such as NIKKISO, DOWA, Seoul Viosys manufacturers, and so on. Chinese researchers of the institutes such as Institute of Semiconductor, Chinese Academy of Sciences, more than 10 years ago have begun the research of this field. Qingdao Jason Electirc CO., LTD., San'an Optoelectronics CO., LTD. and other enterprises have been involved in the field of deep ultraviolet LED technology earlier. Under the leadership of Advanced Ultraviolet Optoelectronics Co., Ltd. and Lu 'an Institute of Semiconductor Technology, Changzhi city Shanxi Province has gradually become the largest concentration area of deep ultraviolet LED industry in China. In recent years, the terminal application products of various deep ultraviolet products have been flourishing.

Guidelines on the Novel Coronavirus-Infected Pneumonia Diagnosis and Treatment clearly points out that the virus is sensitive to ultraviolet rays and heat, quickly moving UV LED towards the public eye. People from all walks of life are paying more attention to regular disinfection, sterilization and purification in their daily lives and work environments. In the long run, with the continuous excavation of application scenes of disinfection, sterilization and purification, ULTRAVIOLET LED will be penetrated in more and more types of household appliances, home, kitchen and bathroom application scenes. In addition, under the background of consumption upgrading, with the decrease of UV LED cost, UV LED disinfection, sterilization and purification will evolve from high additional functions to standard functions of home appliances, household appliances and other application scenarios, which will accelerate the improvement of penetration rate and create a wide market space.

Deep ultraviolet LED will provide abundant sterilization products for people's lives, which will be another industrial reform after the general lighting applications. It will promote the development of the third-generation semiconductor material technology and also provide more guarantees for the lives and health of people all over the world. ■

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ABOUT IOS

IOS has 2 national research centers (the National Research Center for Optoelectronic Technology and the National Engineering Research Center for Optoelectronic Devices), 3 state key laboratories (the State Key Laboratory for Superlattices and Microstructures, the State Key Laboratory on Integrated Optoelectronics (IOS Division), and the State Key Laboratory for Surface Physics (IOS Division)), 3 CAS laboratories (the CAS Key Laboratory of Semiconductor Material Science, the CAS Semiconductor Lighting R&D Center and the CAS Key Laboratory of solid-state optoelectronics information technology). In addition, IOS has the Engineering Research Center for Semiconductor Integrated Technology, the Optoelectronics R&D Center, the Material Science Center, the High-Speed Circuits and Artificial Neural Networks Laboratory, the Nano-Optoelectronics Laboratory, the Optoelectronic System Laboratory, the Laboratory of All-Solid-State Laser Sources and the Component Testing Center.

At present there are more than 680 IOS staff, of whom about 500 are scientific researchers, including 6 CAS academicians, 2 CAE academicians, 28 high caliber researchers from overseas and 16 recipients of the "National Funds for Distinguished Young Scholars". Prof. Huang Kun, an CAS academician and a well-known solid-state physicist, was awarded the "State Top Science and Technology Award" in 2001. Currently, IOS runs three postdoctoral stations, three first-level doctoral programs and three engineering masters training programs.

ABOUT ISA

ISA is an international and not-for-profit organization, registered in Hong Kong, aiming to promote the sustainable development and application of Solid State Lighting (SSL) worldwide. ISA currently has 91 members with more than 4,000 associated members, representing 70% of the output of global SSL industry. ISA members consists of almost all the major players of the global SSL community, including leading industry, academic and application entities.

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Introduction of On-BBL Tunable White Technology

In a traditional tunable white solution with a combination of warm white LEDs and cool white LEDs, the chromaticity point moves linearly on the xy chromaticity diagram, while the black body locus (BBL) is curved. Due to the curvature of the BBL, especially under 3000 K CCT, the emission color withdraws from "white" with a certain range when adjusting the emission color, and it is impractical to prolong the range of correlated color temperature (CCT) toward 2000 K CCT. Tomokazu Nada, Managing Director at ZIGEN Lighting Solution, proposes a new "On-BBL Tunable White" technology that makes the chromaticity point draw an upward curve along the BBL by 2-channel control. This technology expands the possibilities of tunable white LEDs by allowing the CCT range to be set from 2000 K sunset color.

Introduction

After LED technology was adopted in lighting, a tunable white feature that can adjust emission color from warm white to cool white was provided in various lighting applications. And now, a tunable white feature is being increasingly adopted for circadian rhythm lighting.

Generally, emission colors of tunable white LEDs are achieved with a combination of a warm white LED and a cool white LED. The generated chromaticity points are located on the straight line between the chromaticity points of light source.

On the other hand, the set of white points draws an upward curve called the black body locus (BBL), on which the chromaticity points of natural light, like the sun, fire and stars are located. Thus, the farther away the chromaticity points of the two light sources are, the more difficult it is for the chromaticity points of the mixed light to follow the BBL.

For example, if a warm white LED is 2000 K CCT and a cool white LED is 5000 K CCT and both are located on the BBL, the generated chromaticity points in the middle range are more than 7 steps away from the BBL as shown in **Figure** 1. Such chromaticity points are no longer "white".

In order to keep an emission color white, a chromaticity point of a tunable white LED is required to trace the BBL on the xy chromaticity diagram as closely as possible. For this reason, a color range of a tunable white is usually set to the range where the BBL is relatively linear on the xy chromaticity diagram, such as from 2700 K CCT to 6500 K CCT or a narrower range.

However,these days, dim to warm LED technology is becoming popular in lighting and people are now aware of the importance of the 2000 K CCT Sunset Color for comfort and sophisticated lighting effects. Not only that, 2000 K color is said to be very important for circadian rhythm [1]. Thus, it is ideal to implement 2000 K CCT in tunable white lighting applications, despite the problem of the chromaticity point.

One technology to solve this problem is RGB+W LED solution.

Note that W (white color) is necessary on top of RGB (red, green, blue) for a lighting application. Because the spectrums of the RGB LED are separate from each other, the combined spectrum and color quality of the generated light become poor. This means that RGB solutions cannot be used for general lighting applications. By using the RGB+W solution, the chromaticity point can be set at the farthest point on the xy chromaticity diagram, including along the BBL by controlling each R, G, B and W LED output. However, when using the RGB + W solution, each LED output must be precisely controlled to generate a white color. Therefore monitoring intensity from each LED and adjusting output is necessary during operation. The monitoring and adjustment of each LED output is quite complicated and costs are high. Thus, most tunable white LED solutions have, so far, used a combination of warm white LEDs and cool white LEDs, but this is still a compromised solution.

In this article a new technology of tunable white, which starts from 2000 K CCT without the problem of the chromaticity point, even by 2-channel control is presented.

Basics of Color Mixing

A white LED device typically emits with a single CCT and is stable over temperature or current, because

- The wavelength of emission light from a blue LED chip is less susceptible to heat and operating current.
- Phosphor is improved to emit stable spectrum over temperature.

And stable emission color is actually one of the advantages of LED lighting. On the other hand, for achieving tunable white characteristics, it is necessary to arrange at least two sets of white LEDs with different color temperatures (typically, a combination of warm white LEDs and cool white LEDs). By adjusting the current balance between the two sets of white LEDs, the emission color of the mixed light can be tuned.

The chromaticity point of the mixed light is in a weighted position by the light output from the warm white LEDs and the cool white LEDs. Thus, when the light output from the warm white LEDs is higher than the light output from the cool white LEDs, the chromaticity point of the mixed light is closer to the chromaticity point of the warm white LEDs. Also, when the light output from cool white LEDs is higher than the light output from the warm white LEDs, the chromaticity point of the mixed light is closer to the chromaticity point of the cool white LEDs.

In practice, the chromaticity point $(x, y)_{\text{mixed}}$ of the mixed light can be expressed by the following formula, using the chromaticity point $(x, y)_{\text{warm}}$ and the luminous intensity L_{warm} of the warm white LEDs, the chromaticity point $(x, y)_{\text{cold}}$ and the luminous intensity L_{cold} of the cool white LEDs.

$$(x, y)_{\text{mixed}} = \frac{(x, y)_{\text{warm}} \cdot L_{\text{warm}} + (x, y)_{\text{cold}} \cdot L_{\text{cold}}}{L_{\text{warm}} + L_{\text{cold}}} \quad (1)$$

As can be seen from the above formula, the chromaticity point of the mixed light moves linearly between the chromaticity points of the cool white LEDs and that of the warm white LEDs.

Curve Engineering

From the above, it is clear that the chromaticity point of the mixed light by the warm white LEDs and the cool white LEDs cannot draw a curve on the xy chromaticity diagram. Thus, considering the stable color characteristics of white LEDs, no matter which method is used, at least three different chromaticity points from LEDs must be used in order to draw a curve on the xy chromaticity diagram.

It becomes complicated if each LED needs to be controlled separately. One goal is to control three or more types of LEDs by using a 2-channel control so that the chromaticity point of the mixed light moves naturally along the BBL.

To achieve the target, three types of LED strings are provided in an LED module.

- LED string A: connected with a warm white channel
- LED string B: connected with a cool white channel
- LED string C: connected with both warm white and cool white channels

See schematic in **Figure** 2.

The LED strings consist of LEDs connected in series, where the LEDs are LED chips or LED packages. The LED chips in the module are preferably of the same type to

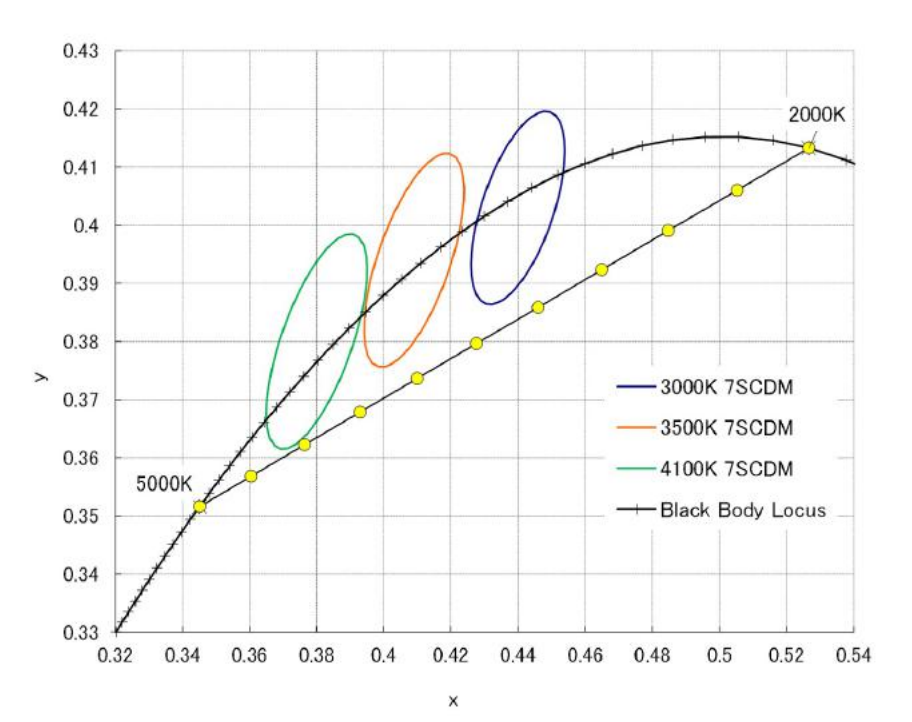

Figure 1: Chromaticity points by conventional tunable white LED together with Mac Adam Ellipse (step-7) on the xy chromaticity diagram

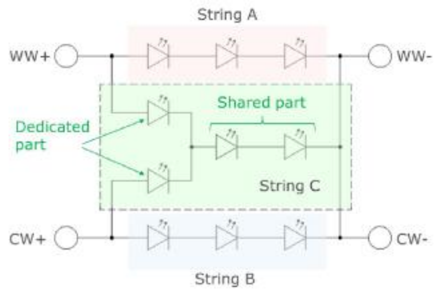

Figure 2: Configuration of "On BBL Tunable White" LED module

facilitate the design and manufacturing of the On-BBL Tunable White LED Module. The emission color of each LED string is set by a phosphor composition of a resin over the LED chips.

The emission color of LED string A is set in the low color temperature range, and the emission color of LED string B is set in the high color temperature range. One pair of electrode terminals connected to LED string A is a warm white channel, and the other pair of electrode terminals connected to LED string B is a cool white channel.

LED strings A and B are individual LED strings that light up when a current is applied to their respective channels. LED string C is a common LED string that is electrically connected to both channels and lights up regardless of the channel. LED string C has a dedicated part and a shared part. The dedicated part is connected to respective electrode terminals and the diode characteristic of the LED prevents a current from flowing through the individual LED strings belonging to the other channel. The shared part is the LED string where a current from both channels flows through. This common LED string plays a key role in the patented "On-BBL Tunable White" technology.

With this constitution, when a current is applied to either channel, one of the individual LED strings and the common LED string light up, and a mixed light is emitted from the LED module. For example, the LED module emits a mixed light from LED string A and LED string C when a current is applied to the warm white channel. Also, the LED module emits a mixed light from LED string B and LED string C when a current is applied to the cool white channel. When a current is applied to both channels, a current flows through all LED strings, and the LED module emits a mixed light from LED strings A, B, and C.

The current balance among LED strings A, B and C changes according to the current balance between the warm white channel and the cool white channel, and the current in each LED string can be described by the following two principles.

1) No current will flow until the applied voltage exceeds the threshold voltage of the LED. This is a typical characteristic of diodes.
2) For circuits connected in parallel, the applied voltage to each string is the same.

When the applied current to the cool white channel is higher than that of the warm white channel, the current to each LED string can be described as below:

In order to carry higher current, the voltage applied to the cool white channel is higher than the voltage applied to the warm white channel, and the current from the cool white channel flows through LED strings B and C. That is, the voltage of the shared part in LED string C is set high enough to carry the current from the cool white channel.

If the voltage applied to the warm white channel minus the voltage of the shared part is less than the threshold voltage of the dedicated LED part to the warm white channel, the current from the warm white channel cannot flow into LED string C (principle 1).

In this case, the light emission from the LED module becomes a combination of the mixed light from LED string B and LED string C by the current from the cool white channel, and the light from LED string A by the current from the warm white channel. The chromaticity point $(x,y)_{BC}$ of the mixed light from LED string B and LED string C lies between the chromaticity points of LED strings B and C weighted by the luminous intensity from LED strings B and C. That means, the chromaticity point of the LED module is located on the straight line between $(x,y)_{BC}$ and the chromaticity point $(x,y)_A$ of LED string A and can be expressed by the following formula:

$$(x,y)_{\text{mixed}} = \frac{(x,y)_A \cdot L_A + (x,y)_{BC} \cdot L_{BC}}{L_A + L_{BC}} \quad (2)$$

This formula is valid as long as the current from the warm white channel is small enough not to flow into LED string C. By increasing the current to the warm white channel, the voltage applied to the warm white channel gets higher.

When the voltage applied to the warm white channel gets higher than the sum of the threshold voltage of the dedicated LED part to the warm white channel and the voltage of the shared part, the current flows into LED string C from the warm white channel. Also, as the current flowing through the shared part of LED string C comes from both channels, the current balance between strings B and C split from the cool white channel is affected.

Because the applied voltages to the parallel circuit is the same, the applied voltages to LED strings B and C (through a dedicated LED part for the cool white channel) are the same, and the voltages applied to LED strings A and C (through a dedicated LED part for the warm white channel) are the same. Thus, knowing If-Vf characteristics of LED, the current through LED strings A, B and C can be simulated. And when the current applied to both channels is the same, that is, the voltage applied to both channels is the same, the current through LED strings A, B and C is averaged.

The higher current that is applied to the warm white channel compared to the current that is applied to the cool white channel, reduces the portion of the current from the cool white channel among the current through LED string C.

And when the current applied to the warm white channel becomes sufficiently higher than the current applied to the cool white channel, the current from the cool white channel will no longer flow to LED string C. The chromaticity point from the LED module can be expressed by the following formula:

$$(x,y)_{\text{mixed}} = \frac{(x,y)_{AC} \cdot L_{AC} + (x,y)_B \cdot L_B}{L_{AC} + L_B} \quad (3)$$

Using If-Vf characteristics of LED string, the simulated result of the currents flowing through the LED strings A, B and C at each current ratio is obtained as shown in **Figure** 3. As can be seen in **Figure** 3, when the current applied to the warm white channel is less than 30% of the total current, the current from the warm white channel does not flow into string C and just flows through string A, because the applied voltage in the warm white channel is not higher than “the threshold voltage of the dedicated part + the voltage applied to the shared part ”. When the current applied to the warm white channel exceeds 30% of the total current, the current from the warm white channel starts to flow through string C. And when the currents between the warm white channel and the cool white channel are equal (at 50% point in the graph), the current to each LED string is averaged.

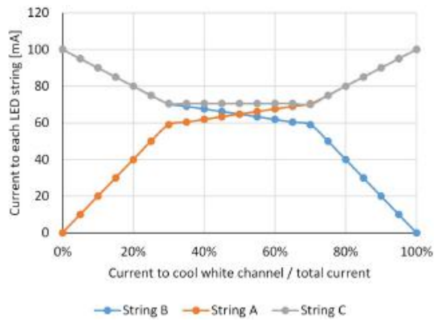

Figure 3: Currents to each LED string at different currents balance out the warm white channel and the cool white channel

To be more precise, LED string C internally has dedicated LED parts connected in parallel, so that a little more current flows through LED string C compared to LED strings A and B when the same current is applied to each channel. Then, the chromaticity point shifts slightly toward the chromaticity point of LED string C, and a rounded curve is drawn instead of a sharp corner. And when the current applied to the warm white channel exceeds 70% of the total current, the current from the warm white channel becomes dominant in LED string C and the current from the cool white channel just flows through LED string B.

Based on the above features, by placing the chromaticity point of light emission from string C below the BBL and placing the chromaticity points of light emission from LED strings A and B above the BBL as shown in **Figure** 4, the chromaticity point of the LED module can draw an upward curve along the BBL.

Results

A Chip-On-Board (COB) LED device with 2-channel input electrodes is prepared as shown in **Figure** 5.

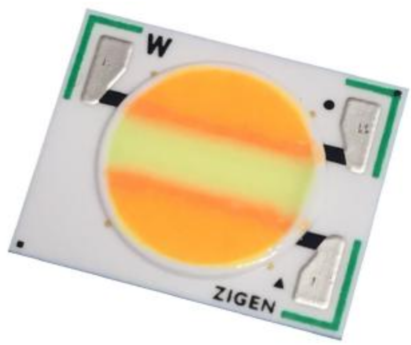

Figure 5: Image of an LED module

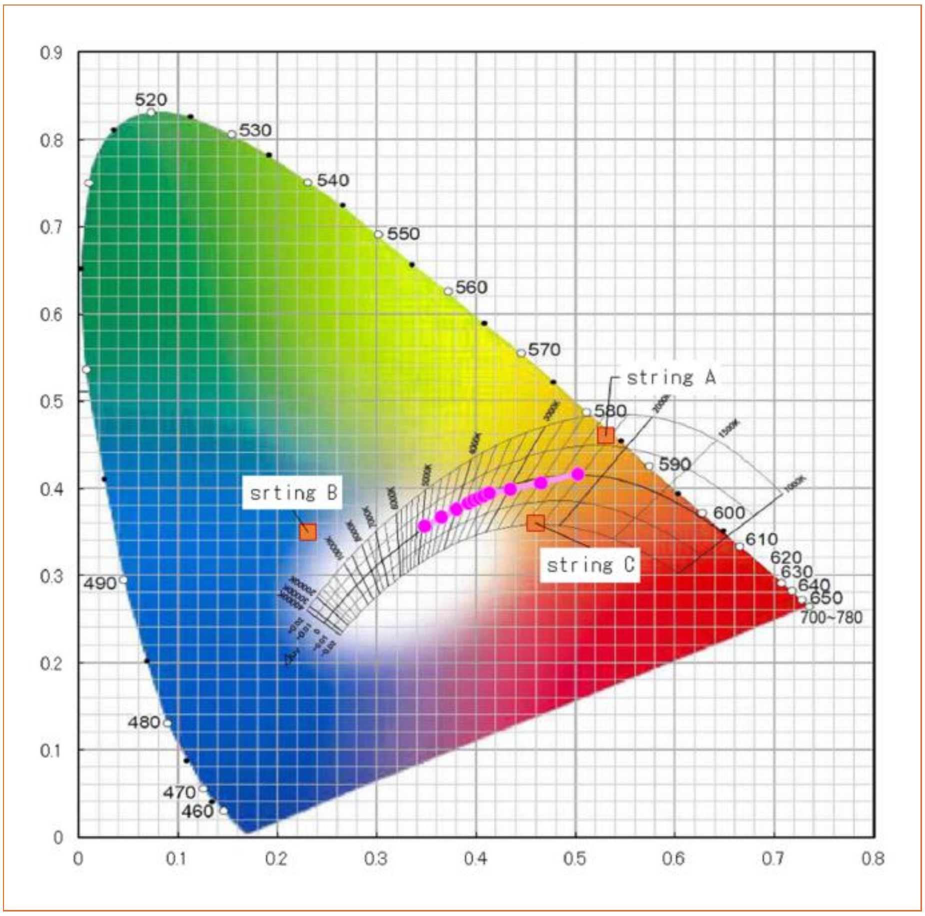

Figure 4: Chromaticity points of LED string A, B and C

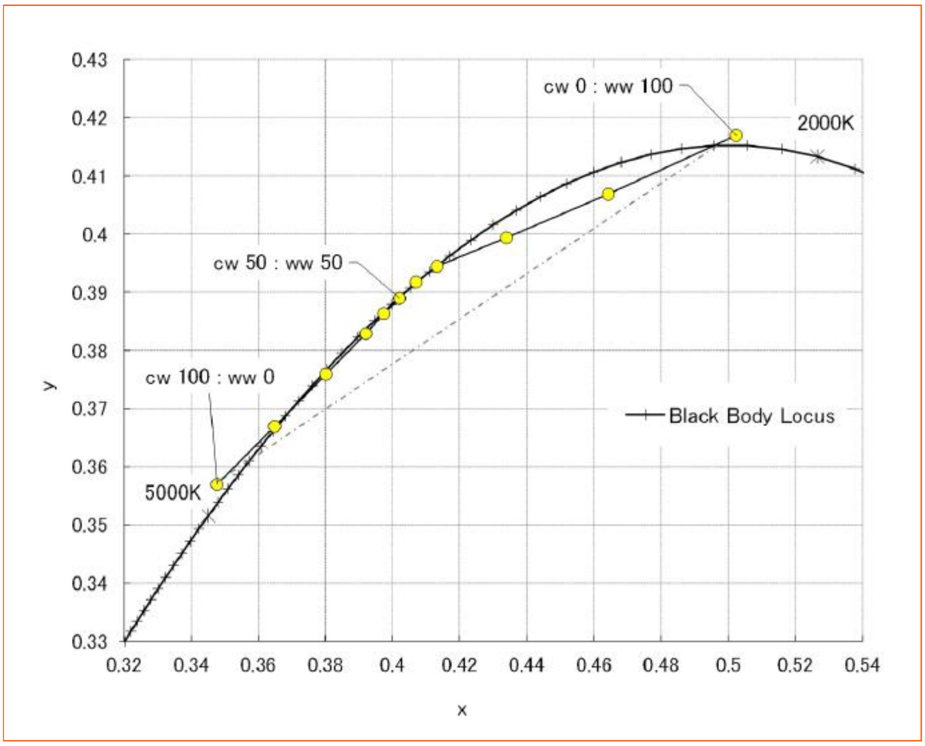

Figure 6: Chromaticity points at different current balance

Common anode is on the left and two cathodes are on the right, one for a warm white channel and one for a cool white channel.

Three kinds of phosphor mixed resin are dispensed to provide individual LED strings for the warm white channel, individual LED strings for the cool white channel and common LED strings. Those LED strings are arranged symmetrically and emit by the targeted chromaticity point.

Figure 6 shows the chromaticity points of the light emission from the COB LED device at different current balance of 2-channel input, together with the BBL.

Due to the phosphor and chip arrangement, the turning point appears at the higher current ratio of the warm white channel. However, it makes sense that the chromaticity point can be located closer to the BBL.

The chromaticity point by the same current to both channels is at a shifted position toward the cool white color side because the light output from the cool white color is greater than that of the warm white color.

As explained, an input current that is sufficiently small compared to the current of another channel just flows through an individual LED string. Under this condition, the chromaticity point of the LED module moves relatively large by the change of the input current ratio.

On the other hand, when the current from both channels flows through LED string C, the current through LED strings A, B and C becomes more averaged. In this condition, the chromaticity point of the LED module moves relatively small by the change of the input current ratio.

Discussion

Application for Panel Lighting

Panel lighting is one of the major applications of tunable white lighting, and SMD type LEDs are mainly used.

By using a 4-color LED set and adopting "On-BBL Tunable White" technology, a wider CCT range along the BBL, such as a range from 2000 K CCT to 7000 K CCT, can be provided. **Figure** 7 shows how the chromaticity point moves from 2000 K CCT to 7000 K CCT by the "On-BBL Tunable White" technology, together with a straight

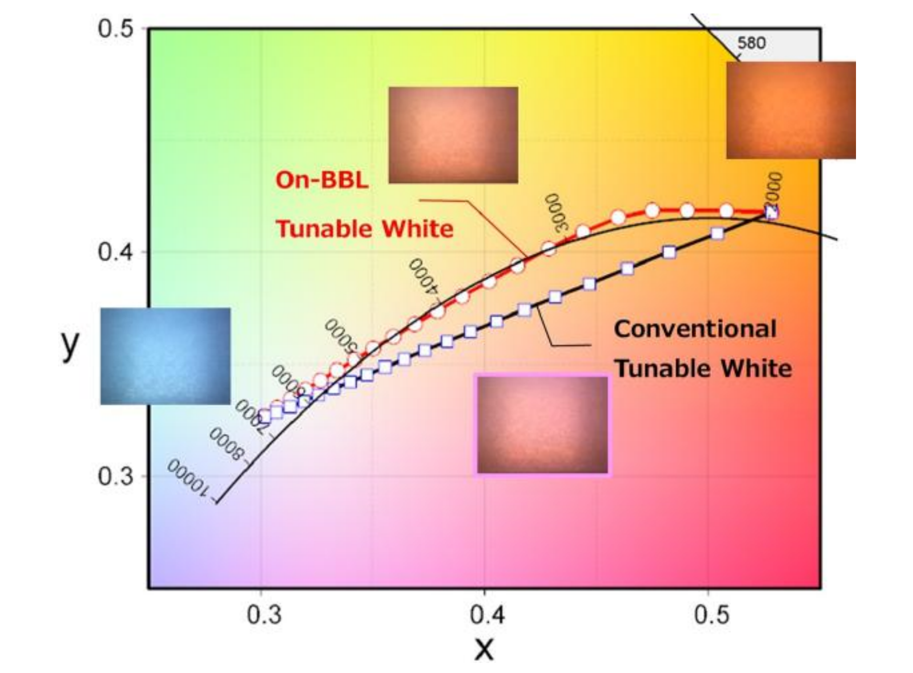

Figure 7: Chromaticity points by "On-BBL Tuanble white" solution and conventional tunable white solution, with images of emission color (CIE 1931)

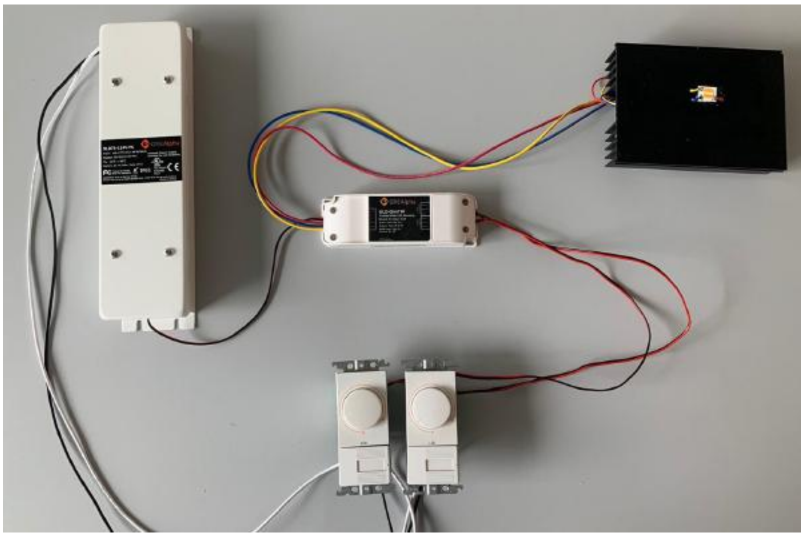

Figure 8: Test circuit

line simply connecting the chromaticity points of 2000 K CCT and 7000 K CCT.

As the images in **Figure** 7 show, the emission color is fairly pink around the 3000 K CCT chromaticity points with the conventional tunable white solution. However, the chromaticity points with "On-BBL Tunable White" technology keep along the BBL, and pinkish color is not observed.

Driver Solution

To achieve the On-BBL feature using "On-BBL Tunable White" technology requires "current overlap from 2-channels" and each channel is driven by a dimmable constant current source. Drivers with 2-channels typically output a current with a PWM (pulse width modulation) control to adjust the ratio of a warm white channel to a cool white channel (**Figure** 8). This means that a current does not flow in the warm white channel and the cool white channel at the same time.

As the currents from each channel do not overlap in LED string C, even with the LED module configured as described in this article, a chromaticity point moves linearly without drawing a curve. Therefore, a driver that complies with "On-BBL Tunable White" technology must split the current into two currents and adjust the current magnitude of the warm white channel and the cool white channel. Or, there is another way to use switching output driver.

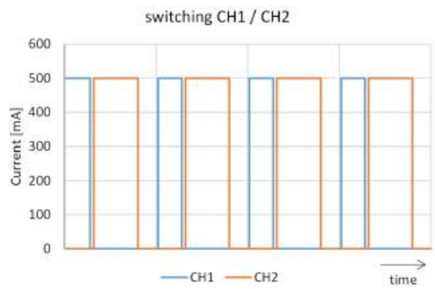

Figure 8: Typical 2-channel driver output

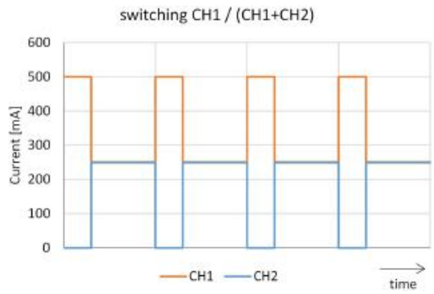

Figure 9: Driver output complied to "On-BBL Tunable White" – Example 1

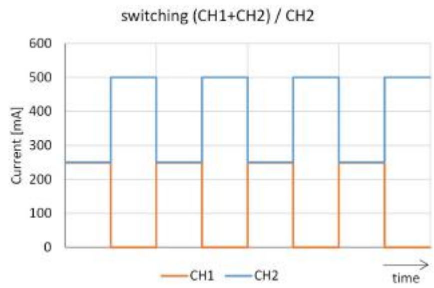

Figure 10: Driver output complied to "On-BBL Tunable White" – Example 2

For example, when the current through the warm white channel (CH1) is higher than the current through the cool white channel (CH2), the output from the driver switches between CH1 and (CH1+CH2) (**Figure** 9). And when the current through the cool white channel (CH2) is higher than the current through the warm white electrode (CH1), the output from the driver switches between CH2 and (CH1+CH2) (**Figure** 10). This creates two straight lines that are close to the BBL. Several companies [3] are developing driver solutions for "On-BBL Tunable White" LEDs.

References

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[2] https://www.nature.com/articles/s41598-019-43864-6
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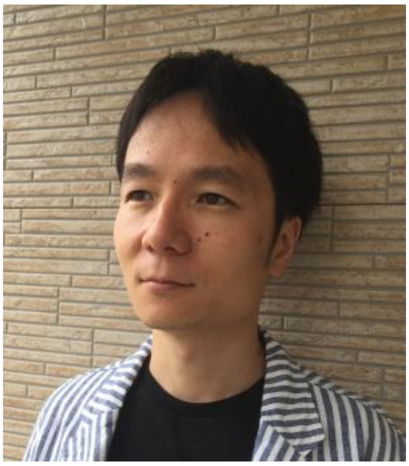
Conclusion

In this article, a new technology to realize "On-BBL Tunable White" with 2-channel control was described.

The principles and configurations are very simple, even though common sense says that the chromaticity point of the emission color by 2-channel control cannot draw a curve along the BBL. In addition, this technology has another advantage which makes more LEDs light up in the limited area of the LED module. In a conventional tunable white LED module, only warm white LED strings light up when a warm white channel is on and only cool white LED strings light up when a cool white channel is on. However, in the "On-BBL Tunable White" configuration, at least 2/3 of the LED strings light up thanks to a common LED string. This helps improve the luminous efficiency of the LED module. As previously mentioned, some modifications to the driver circuit is required, but "On-BBL Tunable White" is one of the key factors that truly benefits circadian rhythm lighting and this solution will expand the possibilities of LED lighting and make contributions to human life through lighting. ■

ABOUT THE AUTHOR



Tomokazu NADA: Nada has a technical background from the LED die level to packaging, due to over 15 years of LED carrier experience at Toyoda Gosei where he was engaged in LED chip R&D, and at SHARP corporation leading the LED COB R&D dept. as well as several innovative achievements, including the invention of dim to warm COB. In 2017, Nada started at ZI-GEN Lighting Solution co., ltd, where he focusses on R&D for innovative LED lighting technolo- gies with a series of products. He is also a technical consultant. He holds several patents including On-BBL tunable white technology. He continues developing further.

Ambient Lighting Design for Persuasive Environments Using Social Media Data

In recent years, social media played a crucial role in informing people around the world about various social/health issues and spreading knowledge leading to increased awareness. It is unfortunate that the actions leading to raised awareness in the social media can only target people inside the digital world but not the people inside the physical space. Since many people deliberately do not take part in social media activities, they remain uninformed and neglected.

In this paper we proposed to use ambient light visualizations to display social media activities surrounding the most relevant social and health issues in public spaces. The aim is to inform people in the physical world, some of whom do not participate in social media, but are eager to learn about different initiatives, thus encouraging them to seek further information about such topics.

It is shown that light visualization has the capability to convey information. Therefore, ambient light displays integrated in public space, can be used to raise awareness by informing people about the amount of attention towards a hot topic in social media in an unobtrusive way by displaying live data gathered from different activities such as the number of shares, comments, and likes. Learning about top social and health issues can encourage people to seek further information about these causes. By providing access to reliable resources via links, QR codes, or other means, people can reach accurate information resulting in raising public awareness.

Introduction

Social media is becoming more and more important in our daily lives. Not only is the number of users of social media growing [1] but also the amount of time people spend on social media networks is increasing [2]. These numbers are only expected to increase. This ever-increasing role of social media in human lives, made it an important platform to be used for raising awareness among people. In recent years social media played a crucial role in informing people around the world about various social/health issues and spreading knowledge leading to increased awareness [3].

It is unfortunate that the actions leading to raised awareness in the social media can only target people inside the digital world but not the people inside the physical world. Many people deliberately do not take part in social media activities. There are a multitude of research and articles showing the concerns about and negative impact of social media on raising awareness. For instance, there is a growing concern about the lack of reliability and quality of the disseminated information on the social media platforms when it comes to healthcare. Furthermore, anonymity or reduced accountability have increased the risks associated with communicating incorrect advice. Even if the information turns out to be factually correct, information overload has made it very difficult for the users to correctly apply the information to their own specific situation [4].

It can now be seen that just like many other technologies, the spread of social media platforms is accompanied with advantages as well as disadvantages. Whether we are in favor of or opposed to the proliferation of social media, trends indicate that this technology is here to stay. Despite its numerous downsides, social media can be used to do good. When it comes to raising awareness in the physical world, visualizing social media data streams has a number of advantages over visualization of the factual information and trends about the cause itself.

For one, social media activity data streams tend to be much more dynamic (changing in real-time) and would thus result in a more attractive and visually pleasing visualization compared to the slow to update data streams that are derived from the governmental or organizational websites. Moreover, studies have shown that simply informing people about various issues, or warning them of the consequences of their actions, is not very effective in encouraging them to change their behavior for the better [5]. However, people tend to act with matching attitudes, beliefs, and behaviors to group norms in a psychological process called Conformity [6]. This can be taken advantage of by displaying the public consensus on various topics.

Various persuasive techniques have been introduced for increasing human awareness using live data, often by informing people explicitly of relevant aspects [7]. An ambient light display could increase human awareness by conveying various information about some of the most pressing social and health issues within a relevant environmental context. Informing people inside an environment is only possible if they can grasp of the meaning of the light visualization.

In brief, the author's aim is to study ambient lighting as a persuasive medium created by social media data streams with the intention to facilitate in raising health and social awareness. The focus of the research presented in this study is on exploring the potentials of using persuasive ambient light created by social media activities, and the possibility of conveying those meanings to the people inside architectural environments.

In order to achieve this goal, it is important to understand, and to investigate the capabilities of light to convey information. Therefore we look at two relevant sets of literature: literature on the fact that social media can play in increasing social/health awareness; literature on the role of light in conveying information; and lastly an experiment examining the possibility of conveying social media meanings though light visualizations.

Social Media vs. Awareness

Before starting to investigate the opportunities of using light to convey the meaning of social media data streams, we first need to understand the role that social media plays in creating awareness, the way individuals and organizations use social media to collaborate in order to promote such awareness, and the most recent and even futuristic approaches for raising awareness in the social media realm.

The Role of Social Media in Creating Awareness: Social Media Activism

Social media has been an enabler of information dissemination, collaboration and coordination for reasons ranging from personal to interpersonal. This has made social media the perfect platform for activism movements. Social media platforms have made mobilizing, coming together, discussing, organizing and protesting much easier than it used to be, especially through the effectiveness and rapidity of online communications, and the accessibility for people from around the world [8].

In social awareness and healthcare, information dissemination is a key mechanism of creating awareness. For instance, it can be a crucial factor in the early understanding of a social issue or detection of various diseases. Specifically, in the healthcare domain, the social media phenomenon has created a new reality in health care, bringing social media to the forefront of health information generation and dissemination. By providing feedback and comments about their experiences with various drugs and treatments, etc., patients and their families have changed from consumers of Internet content to generators of information using social media sites [8].

As briefly mentioned before, this is not always beneficial. There are many risks associated with communicating incorrect advice, information overload, and the fact that such easy access to information may act as deterrent for patients to visit health professionals when necessary. The aim of this research is to be able to provide the information about the trends and relevant activities with regards to healthcare issues and causes, without promoting the direct use of social media, thus taking advantage of its strengths.

The journey of health awareness methods: A road to social media

In the old days creating health awareness happened through a variety of offline strategies, such as collaboration among clinicians from various countries [9] and collaboration through a network of community and university organizations [10] to develop educational programs and campaigns. However, social media has characteristics that enable communication, collaboration, consumption and creation in entirely new ways [11].

Patients and their families use social media as a platform to share their experiences and their findings so others will become educated about similar conditions. They repackage the information they find for others and create forums for knowledge discovery and discussion [12]. For example, approximately two-thirds of posts in Facebook communities dedicated to diabetes include unsolicited sharing of diabetes management strategies and over 13% of posts provide feedback to information requested by other users [13]. Social media provides a forum for reporting personal experiences, asking questions, and receiving direct feedback for people living with a disease. Through social media, support groups have found a new platform for organizing as patients and family caregivers share their experiences and connect with others [14]. Indeed, 620 breast cancer groups exist on Facebook, containing a total of 1,090,397 members. 46.7% of these groups were created for patient/caregiver support [15].

More broadly, it has been shown that social media tools have enabled collaboration among individuals [16]. This can occur in such contexts as employees who work together within the boundaries of formal organizations, to contexts where dispersed individuals connect with one another through the support of a common cause. Now the question is, would social media remain as such an important platform or would it even grow as an important context to raise awareness?

Future position of social media in health awareness

The use of social media for health awareness studies demonstrate that a growing number of educational institutions are emphasizing and training future medical and allied health practitioners on the importance of using social media as an effective means to disseminate information amongst patients and clients. For example, nursing students have been encouraged to move beyond synthesizing pamphlets and flyers as a means of disseminating information to patients and have instead been equipped with resources to create 3-to-5 min YouTube videos to distribute using various social media platforms [17].

Moreover, a recent study demonstrated that utilizing Twitter and Facebook as supplementary tools for delivering educational content can be an effective way to engage medical trainees [18]. According to a recent study, 89% of 291 medical education course participants reported using social media, with most common platforms being YouTube and Facebook [19]. Professional medical societies such as the American Society of Clinical Oncology (ASCO) have been successfully using social media sites like Twitter to report clinical news from scientific sessions, to discuss treatment issues, and to facilitate a broader dialogue amongst physicians and healthcare professionals [20].

Overall, there is a growing pull amongst physicians to utilize social media as a means of ensuring the proper dissemination of information to their patients in order to counteract scientifically questionable publications and educational videos [21]. This means that the quality of the content varies drastically from excellent to spam and misinformation. As the volume of such content increases, the task of identifying high-quality content in social media sites becomes increasingly important and difficult [22]. However, by using social media activity related data streams, such as the engagement level, the most important topics can be identified. This when combined with directions towards a reliable and accountable body of information, steers people away from potential miss-information on the social media platforms and prevents information overload.

Light vs. Awareness

In this chapter, we provide a better understanding about ambient light and its strengths, light as a tool to communicate and the ways of conveying information through visual aids, and lastly some examples of the projects that tried to implement the idea of raising awareness via light visualizations.

Light as a Tool to Convey Information

Since life evolved under the continuous influence of light, it is not surprising that practically all forms of life, including human beings, have developed a variety of responses to light and its characteristics. Light supports human beings functionally: it helps them to observe the world, but more interestingly, to obtain information. In the era we are living in, the integration of sensors, the Internet and lighting created systems that go beyond illumination. In particular, "smart" connected lighting systems have been introduced to the world which are capable of sensing and communicating vast amounts of information. This movement enabled light to become a window displaying those live data and therefore it gained a huge potential for creating context awareness. Also, the varying visual properties of light e.g., color, brightness, saturation, position and frequency of changes [23], made light an ideal tool for encoding and sharing activity information.

Ways of conveying information via light

Light can be visualized in various forms to inform people:

Factual: Light can visualize factual information. Several efforts explored this type of conveying information, which allows users to judge for example levels of household energy consumption by displaying the numbers which represent the home's energy consumption. It has been demonstrated that providing such information could persuade users to use less energy [24]. This type of conveying information needs the most attention among all and will provide detailed information for user.

Graphical: Visualizing information in a graphical way will provide less information for the user, however the information will be conveyed faster and needs less attention to be understood. Earlier research suggested that applying graphical cues in many domains such as child education, health behavior and social interaction has a greater effect compared to the factual ones when the peed of conveying the information matters [25]. For instance, this form of informing has been successfully utilized in a social robot. This robotic agent could show signs of disapproval or negative social incentives (e.g., a sad face or a smiling face) as a feedback.

Ambient: Ambient informing is a subtle and unobtrusive type of conveying information when compared to the previous two methods [26]. Furthermore, participants of an experiment reported that less cognitive effort was needed to understand information conveyed using ambient light thus suggesting that it can be quite cognitively efficient. Ishii and Ullmer (1997) suggested the use of ambient media such as sound, light, airflow, and water movement to act as background interfaces with cyberspace and work at the periphery of human perception. Given this definition, ambient informing has been investigated and applied in practice [27]. For example, an ambient device called Energy Orb (**Figure** 1) was used to provide energy consumption information that changed color dependent on the time of-use tariff in operation (e.g., by glowing red when energy usage reaches a certain level and green otherwise). Another example of an ambient device is the Power Aware Cord (**Figure** 1), which can visualize the current uptake of electricity of a connected appliance through glowing pulses, flow, and intensity of light [28]. The aim of the Power Aware Cord is to inform the user about the current consumption of various devices and thus persuade them to buy or use more power efficient types/brands.

Figure 1: Energy Orb (left) and Power Aware Cord (right)

Since in this study we are using ambient light as the persuasive technology for raising awareness, in the coming sections we are going to look deeper into the ambient light and its role in creating awareness.

Ambient Light: As a Peripheral Awareness Tool

The concept of ambient visualization or ambient display is defined as a category of data representations that conveys time-varying information in the periphery of human attention [29]. Peripheral vision, or indirect vision, is a part of vision that occurs outside the very center of gaze [30]. Receiving information via light in a peripheral way will create several opportunities:

Prevents information overload: when compared to factual and graphical visualizations, ambient displays can remarkably reduce the amount of information mentally processed by providing an overview of the content by having information subtly portrayed in the periphery of one's attention [31]; meaning that people can perform their primary tasks in the foreground while simultaneously receiving context information in the background of their attention. It can be beneficial specially in the era that people often experience "information overload".

Capture more audience: Since ambient light is detectable by the periphery vision of human beings it can help increase awareness by grabbing the attention of more people. Conveying information in the peripheral field of vision (**Figure** 2), which allows us to see without turning our head or moving the eyes [32], can spread among higher amount of audiences.

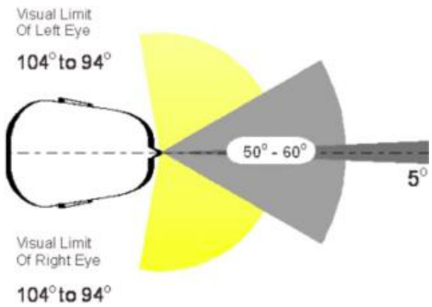


Figure 2: Horizontal field of view (yellow field shows the peripheral vision)

Data driven ambient light: Creating ambient communication

Using ambient visualizations created by live data to convey information creates ambient communication within architectural environments. Light acts as an interface between the digital world and the psychical world, and the benefits for using digital content for lighting could be to render the invisible visible [33]. It could mean visual representation of weather, air traffic, social media traffic and much else in a calm and abstract way. When information transfers in an ambient manner, it does not draw attention, but it seeps in; we as humans have a huge ability to take that information in [34].

Such communication technology can be helpful in raising awareness. For instance, in the health domain, where users have to maintain an active lifestyle by tracking physical activity [35] or it can help in increasing awareness about maternal health [36]. Furthermore, in the domain of environmental sustainability, persuasive technology could create "energy awareness" [37]. More examples of such ambient informing are as follows:

Particle Falls: This project reveals the presence and impact of particle pollution through a real time artistic visualization on the side of the building, in the form of a waterfall. The brighter and stronger the waterfall appears, the higher the concentration of particles in the air [38]. The vision for this project was to raise awareness amongst the public about air pollution. Since it measured in real time, it was able to show directly in what way human activity can make the air quality worse.

Figure 3: Particle Falls project

Human BEEing: This temporary project demonstrates the use of digital place-making technologies not only for connecting people with their cities, but also for raising awareness of global pressing issues [33]. The project wanted to draw attention to the very important role that bees play, pollinating plants and producing honey.

Figure 4: Human BEEing project

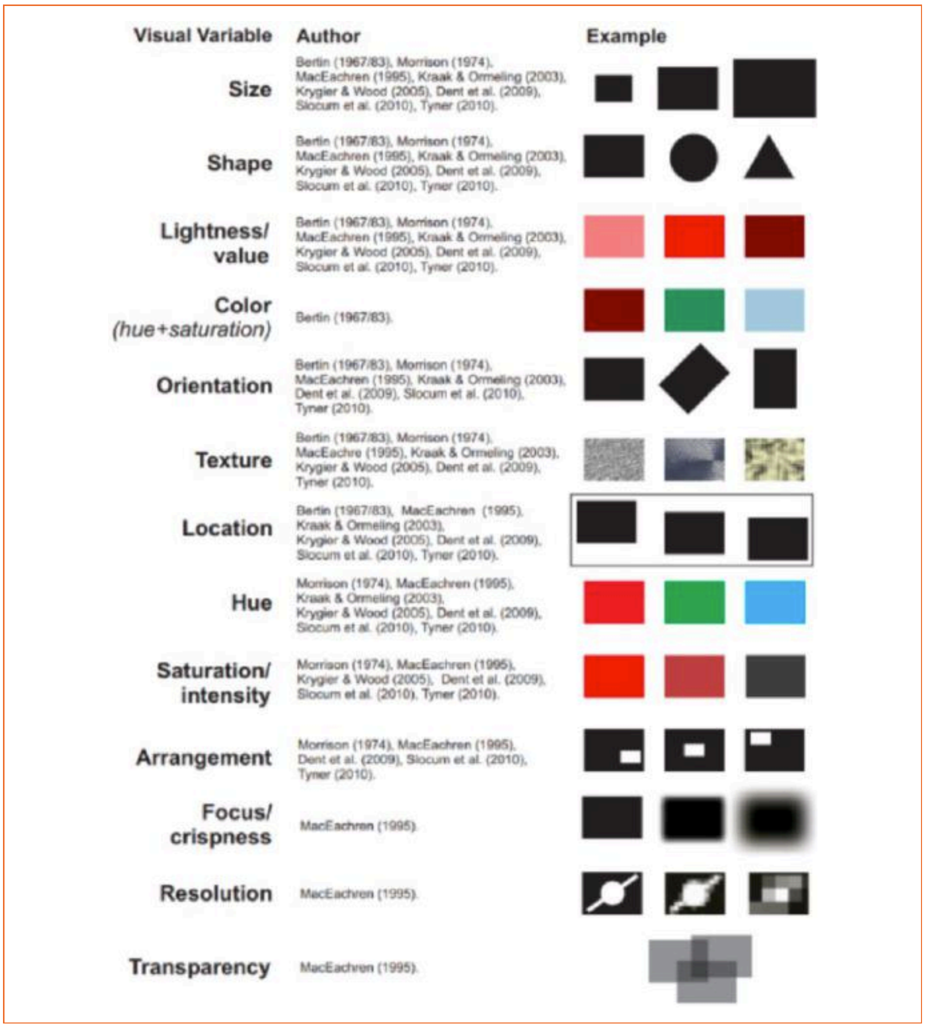


Figure 5: Breakdown of static visual variables

Light Visualizations vs. Social Media Meanings

In this study, we decided to spread awareness regarding the top used Hashtags among the people in the physical world using ambient light visualizations. Since the main intention is conveying the meanings of social media activities to the people, it is important to investigate the understanding of the people regarding different light visualizations. Therefore, in this chapter a test has been designed to evaluate the possibility of informing people about social media activities through light.

The hope is that the result of the test can be used directly to construct a visual language for expressing social media activities. However, the ultimate goal of the test, is to conclude whether it is possible to convey the meaning of concepts of social media, using light visualizations.

Background

Visual variables

In order to prove that ambient light is able to convey information, we need to understand how we can encode information in the form of light visualization. This section contains a review of literature which examines the visual variables that can be varied to encode information. These variables can be divided into two groups: static variables that describe the graphic dimensions that are invariant to time [39], as well as dynamic variables that encode information in the temporal dimension. The final goal is to compile a list of suitable visual variables that can be played with to create the visualizations.

Static visual variables: "The nature of the pigments provides the basis for sensations of light and color; that is, brightness, hue and saturation. The geometrical demarcation of these qualities provides the physical basis for perception of areas and their shapes. Altogether, these factors constitute the vocabulary of the language of vision, and are acting as the optical forces of attraction." [40]. In this quote, Gyorgy Kepes, lists several visual attributes. These visual factors have been picked up by many designers and authors ever since. Jacques Bertin subsequently extended and proposed a new list that contains: position, direction and differences in size, shape, brightness, color and texture. **Figure** 5 outlines the visual variables that have been added to the language of vision in the field of cartography.

Thus, given the mentioned literature, a list of static visual variables was compiled. **Table** 1 provides an overview of these variables which covers the primary variables that are mentioned and used by the researchers.

Dynamic visual variables: Even though Bertin did not have a lot of confidence in the usefulness of dynamic maps, he stated that motion would dominate the graphic

Variable	Description
Size	Size describes the amount of space occupied by the graphic object.
Shape	Shape describes the external form (i.e., the outline) of the graphic object. The shape can vary from highly abstract, such as circles, squares, or triangles, to highly complex geometries.
Lightness	Lightness describes the relative amount of energy emitted or reflected by the symbol. Variation in color value results in the perception of shading, or areas of relative light (high emission) and dark (low emission). Accordingly, color value is sometimes referred to as "lightness" in color theory.
Color hue	The degree to which a stimulus can be described as similar to or different from stimuli that are described as red, green, blue, and yellow. This is one of three visual variables associated with the perception of "color."
Color saturation	Saturation is the "colorfulness of an area judged in proportion to its brightness", which in effect is the perceived freedom from whitishness of the light coming from the area [20]. This is the third of three visual variables associated with the perception of color. Bold or saturated colors emit or reflect energy in a concentrated band of the visible spectrum, whereas pastel or desaturated colors emit or reflect energy evenly across the visible spectrum.
Orientation	Orientation describes the rotation of the graphic object from "normal." The normal orientation typically is relative to the neat line (either explicitly included or inferred by negative space), but in some cases it can be relative to the projected spatial coordinate system.
Texture	Texture is a higher-order visual dimension with three constituent components: the directionality of the texture units (related to the visual variable orientation), the size of the texture units (related to the visual variable size), and the density of the texture units (approaching the perceptual effect of shading associated with the visual variable color value).
Location	Location describes the position of the graphic symbol relative to a frame.
Arrangement	Arrangement describes the layout of graphic objects constituting the whole. The visual variable arrangement varies from regular to irregular.
Crispness	Crispness describes the sharpness of the boundary of the graphic object. Crispness also is referred to as the inverse of "depth-of-field" and "fuzziness" in information visualization.
Resolution	Resolution describes the spatial precision at which the graphic object is displayed.
Transparency	Transparency describes the amount of graphic blending between a graphic object and the background or underlying graphic objects.

Table 1: Definition of visual variables [41]

variables he distinguished (size, value, grain, color hue, orientation and shape), thus revolutionizing the effectiveness of the field of cartography. Recent research confirms Bertin's opinion by showing that visual variables can indeed be used on the individual frames of an animation in such a way that these images effectively communicate a message to the user, while the movement of the animation gives the message an extra dimension and "new energy" [42]. Furthermore, the findings of Koussoulakou showed that using animated graphics helped users grasp the contents of a message in a more effective manner compared to using traditional static visualizations [42].

It has become clear the the static visual variables are not sufficient to describe the added depth of information that we have available today. To this end, six "new" dynamic visual variables were introduced by MacEachren in 1994 [44]. These are: moment, duration, frequency, order, rate of change, synchronization. **Table** 2 provides an overview and description of these variables.

Data categories

In this study, it is intended to represent social media activities. The changes and trends in this data is what we want to convey using ambient light visualizations. However, social media platforms have a wide range of data streams. To simplify, we can attemt to categorize these data streams based on their sililarities. It is hoped that the same visualization can then be used successfully to convey the meaning of any of the data streams within the same category.

In order to come up with a reasonable number of categories to assign to different data streams, 5 of the most commonly used social media platforms (Facebook, YouTube, Instagram, Twitter, LinkedIn) [45] was selected. Subsequently, a list of all of the data streams for each social media platform was compiled and clustered based on similarities. Finally, according to the literature study regarding the different social media categories, the most appropriate names have been assigned to the clusters which resulted in the 9 data outlined in **Table** 3.

Methodology

This section provides an overview of the methods and procedures used in the test. This should allow future researchers to reproduce and extend the experiment in order to improve upon the results achieved within the limited time and scope of the project. A detailed description of the visual stimuli, participants and test procedure is outlined below.

Stimuli

A number of static and dynamic visual variables were identified in the previous section which can be used to encode information. According to the literature study, these variables are: Size, Shape, Color value, Color hue, Color saturation, Orientation, Texture, Location, Arrangement, Crispness, Resolution, Transparency, Moment, Duration, Frequency, Order, Rate of Change, and Synchronisation.

Given the fact that the visualizations are intended to be displayed using a screen, some of the aforementioned variables are either impossible to demonstrate or reduce to the same variable. In this test, it was decided to use a vertical line as the main graphic object. This fixes the variables Shape and Size, thus removing them from the design space for developing the visualizations. This was done to reduce the scope and thus the complexity of the test by a considerable margin. A line is the simplest geometrical shape (it's considered one dimensional in this context) which is the reason why it was selected. Any shape that defines both a vertical as well as horizontal boundary would also require 2 parameters to define its Size and Location. While a line requires one (width and

Variable	Description
Moment	The moment that a graphic object changes during an animation can be used for temporal as well as non-temporal animations.
Duration	Duration indicates the duration in real-time a graphic object is visible during an animation. For instance, if province A has twice the amount of annual sunshine of province B, province A would be highlighted twice as long during the animation.
Frequency	The dynamic visual variable frequency uses the rate of occurrence of graphical elements.
Order	Animation actually is the presentation of individual frames in a given order. Chronologically showing temporal data is probably the most used form of animation.
Rate of change	The rate of change can be described as M/D, where M is the change magnitude and D is the duration for that change.
Synchroniza	With synchronization two (or more) phenomena are related to each other by showing their development synchronously in one animation.

Table 2: Description of Dynamic Visual Variables

Data Category	Description
Reach	Number of times a post has been exposed to the users.
Approach	Number of clicks in order to view a post.
Transience	Ratio of average minutes watched per view over the total time length of the post.
Engagemen	Ratio of the number of likes and comments over the 'total number of views' (approach).
Distribution	Ratio of the number of shares and mentions over the 'total number of views' (approach).
Growth	Change in the number of followers, friends, or subscribes.
Achievemen	Special event, like when a post receives the highest number of likes.
Historic Legacy	The number of times a Hashtag has been used or searched for.
Compositior	Arrangement of the users' specifications, like gender.

Table 3: Data categories' definitions

position along the horizontal axis) making it easier to map to most quantitative information. This leaves room for improvements in future research.

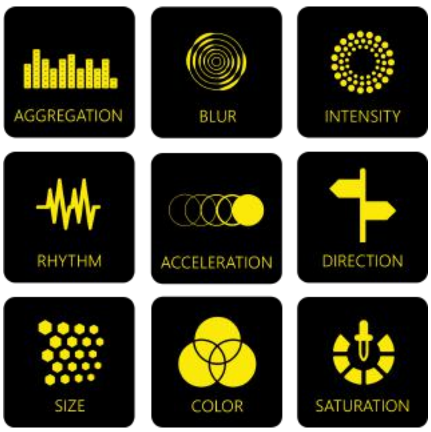


Figure 6: Visual variables selection to create light visualizations

Furthermore, Texture is also eliminated as variable as the aim of the project was to communicate information using ambient light. Light reflecting off a surface cannot represent Textures. The visible Texture is a property of the surface reflecting the light and its control is out of the scope of this test. Focus and Resolution carry the same effect when it comes to visualizing with light; therefore, in this study Focus has been chosen since it has a better similarity to blurriness which is a light property. Similarly, Transparency and Lightness (of the foreground graphic object), as defined in the previous section, become equivalent when using light visualizations.

Lastly, regarding the dynamic visual variables, due to the complexity and the number of visualizations required to cover all these variables, it was decided to focus on a few of the more distinct variables. Synchronization was not used as only a single graphic object (the line as described above) is displayed. Furthermore, Moment and Duration represent two sides of the same coin and thus are captured on every visualization as such there are not isolated in their own specific visualization.

Due to the above reasoning, the final selection of the visual variables for creating the light visualizations for this test are as below: Size, Lightness, Color, Location, Saturation, Focus, Moment, Frequency, Order, Rate of change. From these variables, 9 visualizations were created (**Figure** 6). These visualizations are designed to incorporate and display one or more of these variables. Since, these variables are varied frame by frame, it is vital to also consider the inverse order for each visualization. Hence, each visualization is created as a pair of converse animations.

Procedure

With a set of light visualizations and data categories at hand, we can establish a test procedure to explore which data category the participants would perceive after watching each visualization. The test consists of two phases: Answering an online questionnaire as well as the complimentary interview. At first, a short introduction is provided to each participant. The aim of the introduction is to explain the meaning of the social media categories, as well as the test procedure and survey layout. Next, the participants will be asked to fill in an online survey after reading and signing the informed consent form. The participants were also given an estimation of the time required to complete the questionnaire and an e-mail contact in case they had any questions or doubts.

SogoSurvey was used as the online platform to host the questionnaire. There are 18 questions in total, each corresponding to a particular visualization. At the top of each question, a short (5 second) visualization is displayed. The video is looped in case the participants want to have another look. It is important to note that before the start of the visualization, a brief message is displayed that counts down to the start of the visualization. This is done in order to ensure that a constantly repeating visualization does not produce unintended effects (such as conveying frequency).

Furthermore, the order of the questions is randomized to improve the accuracy of the results. This also helps combat the effect of participants losing focus at the end of the survey, thus providing less elaborate answers for the latter questions. Below each visualization, the participants have the ability to select one or more data categories that they perceive as being related to the displayed visualization. Each selection can be elaborated using a textual answer.

The next phase of the test is an interview with the participants. This will take place after the results of the participant was briefly analysed. This is done in order to focus on the more interesting answer due to time restrictions. The aim of the interview is to clarify any ambiguities in the provided answers as well as gaining other insights that may be triggered after a one to one conversation. It is important to only perform the interview after the survey has been fully completed, as to not influence the results.

Participants
In total there were 18 participants that took the survey. All participants were TU Delft students, out of which, 8 were female and 10 were male. The age of the participants was between 21 to 31 with an average of 25. The participants originated from 8 countries, 3 of which are located on the European continent, 2 in America and the final 3 in Eastern Asia.

Results

To be able to draw valid conclusions from the data collected through the experiment, it is important to summarize, process and visualize the data in a form that can best be analyzed. The analysis is broken down into two parts. The first part examines if each of the 18 visualizations can be used as an effective method for conveying the meaning of one of the selected data categories. The distribution of the votes between the data category trends is the subject of the second part of the analysis. There, the possibility of using the 18 selected visualizations, as a means of conveying a sense of increase, decrease or constancy (here after referred to as data category trend) is examined. In each section, a quantitative analysis is performed based on the gathered numerical results (the number of votes for data categories and data category trends), as well as a qualitative analysis based on the interviews.

Visualizations vs. data categories
This part examines if each of the 18 visualization can be used as an effective method for conveying the meaning of one of the selected data categories. This is done by observing any outliers that fall outside of the normal distribution of the dependent variable. The following sections are the conclusions derived from the analysis:

1. Aggregation: This pair of visualizations is a good candidate to be used for representing Distribution in later designs, since both the normal and inverse visualizations conveyed a meaning of increase/decrease in Distribution. Furthermore, when considering the qualitative analysis, Growth and possibly Reach may present other alternatives. Moreover, due to the explanation of the meaning of Reach, this data category can only increase therefore can be represented through the first visualization (Aggregation_Normal).

2. Blur: Unfortunately, this pair of visualizations do not share any common data categories. This means that even though each visualization by itself may be used to convey Growth or Transience, it is not very wise to use this pair to convey and increase or decrease in any of the data categories. The qualitative analysis also confirms the quantitative analysis. Blur_Inverse can however be employed by itself for conveying Transience (for instance approaching the end of something).

3. Intensity: The results show that this pair of visualizations is an ideal candidate to convey Growth. The converse pair also performs very well when conveying a sense of increase or decrease leaving little ambiguity when it comes to these two visualizations.

4. Rhythm: Unfortunately, this pair of visualizations do not share any common data categories. This means that even though each visualization by itself may be used to convey Engagement or Transience, it is not very wise to use this pair to convey and increase or decrease in any of the data categories. The qualitative analysis also confirms the quantitative analysis.

5. Color: This pair of visualizations is a good candidate to be used for representing Composition in later designs. However, nothing can be concluded regarding the trend of the data category. Most people perceive cannot associate a change in color to an increase or decrease. This fact is quite intuitive when considering the fact that composition is defined as a ratio of constituents where the total is always constant.

6. Direction: Reach is the only common data category that can be conveyed using this pair of visualizations. The qualitative analysis also shows that given a similar target group (with regards to the native language they use) a sense of trend (increase/decrease) can also be reliably conveyed.

7. Saturation: Adding the insights gained from the qualitative analysis as well as the results from the quantitative one, Achievement is the leading candidate to be conveyed using this pair of visualizations. Composition is another alternative data category that may be used successfully.

8. Acceleration: This pair of visualizations do not share any common data categories. Even though the two visualizations by themselves may be used to convey Reach, Engagement or Growth, it is not wise to use this pair to convey an increase or decrease. The qualitative analysis combined with the quantitative results, suggest that Growth can be conveyed somewhat successfully, but further research is required.

9. Size: This pair of visualizations do not share any common data categories. Even though the two visualizations by themselves may be used to convey Reach, Approach or Growth, it is not wise to use this pair to present any of the data categories. The qualitative analysis, combined with the quantitative results, suggest that these visualizations are excellent for conveying a trend (increase/decrease) however.

Visualizations vs. data category trends
The distribution of the votes between the data category trends is the subject of the second part of the analysis. In this section, the possibility of using the 18 selected visualizations, as a means of conveying a sense of increase, decrease or constancy (here after referred to as data category trend) is examined.

Increase/Decrease: The key in finding a good visualization for conveying a sense of increase or decrease is to find a pair of converse visualizations that show an inversely proportional relationship when we observe its number of votes. To clarify, this means that whenever a visualization receives a high number of votes for increase, its converse visualization should receive a low number of votes. Similarly, when looking at the number of votes for decrease, this pair of visualization should present the opposite results. Any pairs of visualizations that this illustrate behavior is an ideal candidate to convey increase and decrease in a reliable manner.

It has been observed that the following visualizations received more votes than the mean and median value: Aggregation, Blur (inverse), Intensity, Rhythm (irregular), Saturation, Acceleration and Size. Out of these visualizations, the number of votes for Aggregation, Intensity, Acceleration and Size show a statically significant result. Furthermore, their converse visualization has a number of votes that are far below the mean and median. These four visualiza-

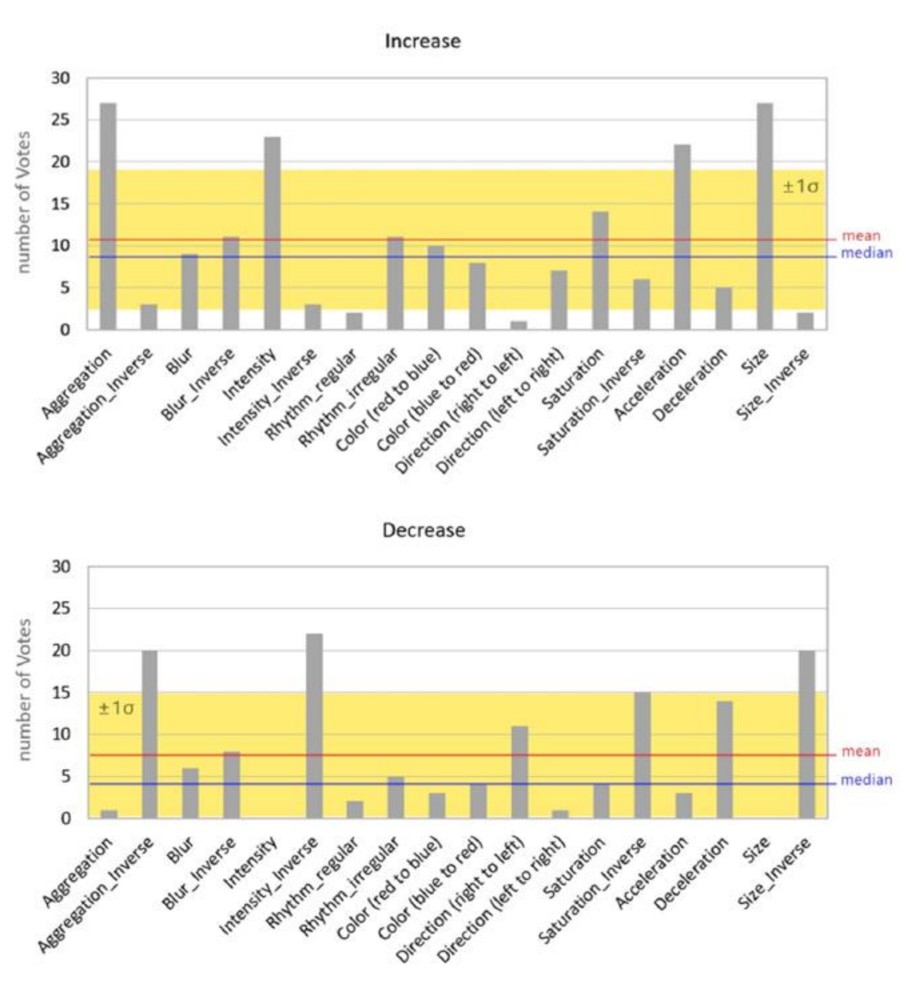


Figure 7: Increase (top) and Decrease (bottom)

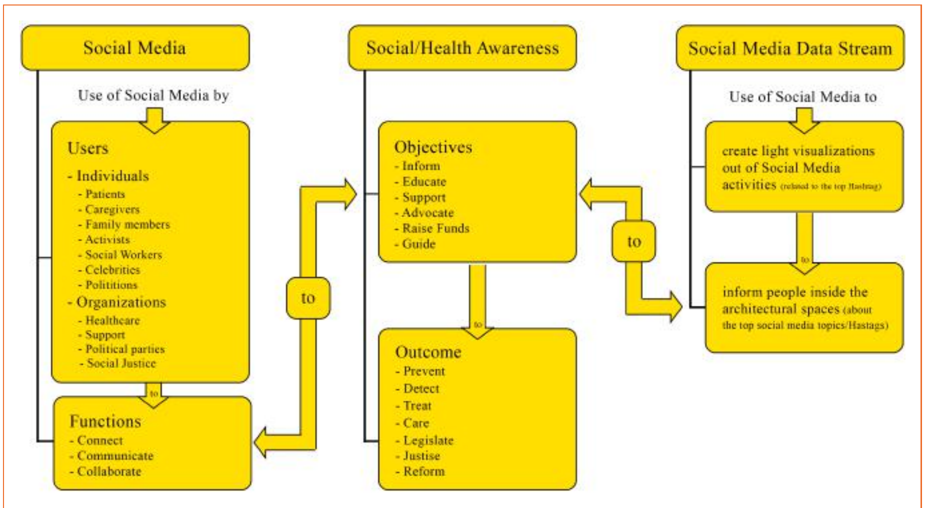


Figure 8: Diagram showing awareness increase through not only informing in social media, but also via light visualizations in the physical space

tions are excellent candidates to convey a sense of increase.

On the other hand, Aggregation (inverse), Blur (inverse), Intensity (inverse), Direction (left to right), Saturation (inverse), Deceleration and Size (inverse) have received more votes than the mean and median values.

Out of these visualizations, Aggregation (inverse), Intensity (inverse), Saturation (inverse) and Size (inverse) show statistically significant results by obtaining enough votes. Moreover, their converse visualizations have received less votes than the mean and median value of votes.

Comparing the above two sets of visualizations (see **Figure** 7), it can be observed that Aggregation, Intensity and Size are form pairs of visualizations that indeed display the all of the requirements to be used as a method to convey a sense of increase and decrease reliably. Though not as statically significant, the results hint that Saturation and Acceleration can also be used successfully for this purpose. As mentioned before, interviews show that the color used to display Saturation and the direction of motion for Acceleration play an important role in how they are perceived. Further research is advisable to draw more concrete conclusions with regards to the suitability of these two visualizations.

Constant: If one needs to convey the meaning of one the selected data categories without an associated sense of increase or decrease, which visualization is suitable? This section aims to answer this question. From the test results, it can be observed that the following visualizations received more votes than the mean and median value: Blur (inverse), Rhythm (regular), Rhythm (irregular), Color (red to blue), Color (blue to red) and Direction (left to right). With the exception of Blur and Direction, the other 4 visualizations form a pair (Rhythm, Color), meaning that both the normal as well as the converse visualizations do not seem to convey any sense of increase or decrease. These visualizations can be used with other visualization to provide additional information without affecting the overall sense of trend.

Conclusions

After demonstrating the crucial role of social media in informing people around the world about various social/health issues leading to increased awareness, and focusing on the neglected people who are not the users of social media, it has been decided to inform people in physical spaces about various hot topics inside the digital space. As a result, more people can become aware about different social/health issues (**Figure** 8).

In this paper, ambient light visualization was used to expose the social media activities relevant to the top social and health issues, in public spaces. The goal was to inform people in the physical world, some of whom do not participate in social media but who are eager to learn about different initiatives, about the most pressing issues. Thus, encouraging them to seek further information about such topics. To prevent the promotion of social media, the public displays of ambient light can be accompa-

Data Category	Description
Reach	Aggregation (Normal), Intensity (Normal), Direction (Left to Right), Direction (Right to Left), Acceleration (Normal), Size (Normal)
Approach	Rhythm (Regular), Size (Normal)
Transience	Blur (Inverse), Rhythm (Irregular), Direction (Right to Left)
Engagement	Rhythm (Regular), Acceleration (Normal)
Distribution	Aggregation (Normal), Aggregation (Inverse)
Growth	Blur (Normal), Intensity (Normal), Intensity (Inverse), Direction (Left to Right), Acceleration (Inverse), Size (Inverse)
Achievement	Color (Red to Blue), Saturation (Normal), Saturation (Inverse)
Historic Legacy	–
Composition	Color (Red to Blue), Color (Blue to Red), Saturation (Normal), Saturation (Inverse)

Table 4: Selected Visualizations for each Data Category

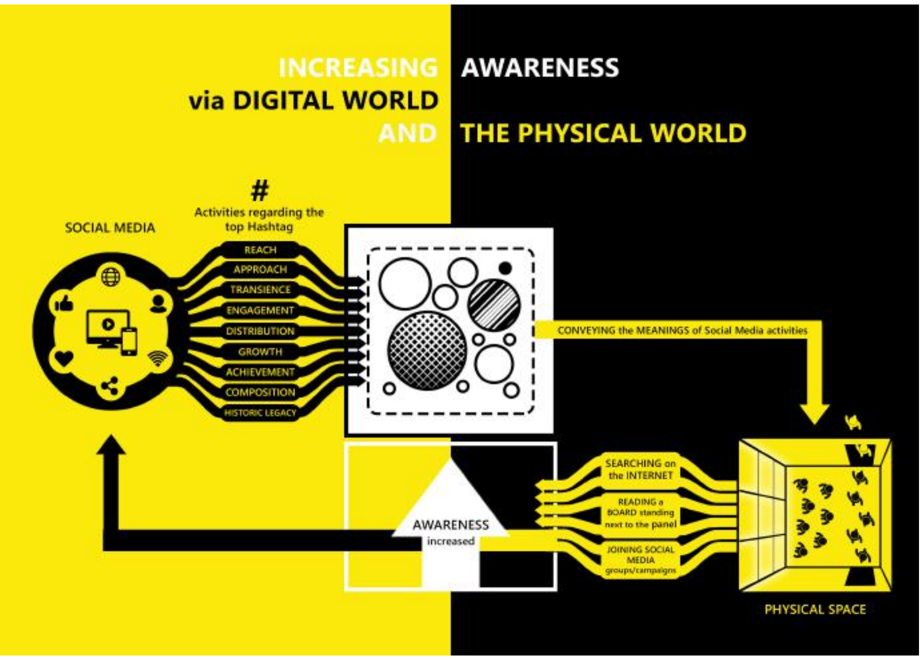


Figure 9: The journey of informing people inside physical world resulting in raising awareness

nied with additional links to resources that are determined to be of high quality. This is an important factor as research has shown that part of the information that is disseminated on the social media platforms is of a lower quality compared to those generated by professionals.

Moreover, ambient light communication was used as the method for conveying this information. Understanding ambient light communication and the opportunities it can bring to human lives demonstrates that light has the potential to add a new layer to the environment, in a way that serves information and this information can be used for various applications. It was shown that ambient light requires less cognitive effort from people and it produces a higher impact on their behavior. When compared to factual and graphical visualizations, ambient displays can reduce the amount of information mentally processed by providing an overview of the content by having information subtly portrayed in the periphery of one's attention; meaning that people can perform their primary tasks in the foreground while simultaneously receiving context information in the background of their attention. Furthermore, since ambient light is detectable by the periphery vision of human beings it can help to increase awareness by grabbing the attention of more people.

To achieve our objectives, it was vital to show that the concepts of social media streams can be conveyed in an effective manner using ambient light visualization. To this end a set of light visualizations and social media data categories was identified and selected. An experiment was established to explore which data category the participants would perceive after watching each visualization. The results, which in summary is demonstrated in **Table** 4, showed that most participants did indeed have a common perception of some of the data categories. This means that the participants shared a common understanding of these visualizations which suggests that in more general terms, light visualization can be used to form a very basic language to transfer information.

The results of the test for some of the data categories were more concrete than others. For instance, Distribution, Growth and Composition are best displayed using Aggregation, Intensity and Color, respectively. Achievement can be conveyed by using Saturation provided more that an appropriate color is selected. This of course is a good subject for further study. Furthermore, Transience can be displayed successfully by Rhythm if there is no need to also convey a trend in this data category.

The results also showed that a pair of converse visualizations may be used for conveying two different data categories. For instance, Acceleration and Deceleration can display Engagement and Growth, respectively. This knowledge can be applied in more specific cases by designers. Lastly, it was also shown that data trends (increase/decrease) are best expressed using Aggregation, Intensity and Size, and that people tend to get a sense of constancy from a shifting color or regular/irregular movements. This experiment does not fill every gap in our current understanding of the subject. In contrary, a lot more research is required in this area to be able to define the building blocks for this new language. However, the results of the experiment should provide a solid foundation for future researchers.

In conclusion, we showed that ambient light visualization integrated in public displays, can be used to raise awareness by informing people about the amount of attention towards a hot topic in social media in an unobtrusive way by displaying live data gathered from different activities such as number of shares, comments, and likes. Learning about top social and health issues can encourage people to seek further information about these causes. By providing access to relevant resources via links, QR codes, or other means, people can obtain accurate information, resulting in raising public awareness, which, hopefully, would encourage them to act respectively (the process is demonstrated in **Figure** 9). ■

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When Circular Economy Meets the Lighting Industry (LCA)

The work presented in this paper is part of the Repro-light ("Re-usable and re-configurable parts for sustainable LED-based lighting systems") European research project, which aims to successfully initiate a transformation in the European LED lighting industry in the year 2020. The project harnesses innovative production technologies (Industry 4.0) and materials to produce a modular luminaire architecture with a smart production scheme that is designed considering the aspects of a circular economy. The Repro-Light LED luminaire is reconfigurable, dimmable and customizable, and aspires to be the 'Luminaire of the Future'.

In order to make a positive impact in the European lighting industry, the Repro-Light LED luminaire design aims to make improvements to the environmental impact of LED luminaires, as well as to reveal the possible economic and social benefits of designing for circularity. In terms of the environmental impact, it is important to remark that great efforts have been done in the past to reduce the energy consumption of lighting during its use phase. However, LED luminaires have a specific material composition, consisting of electronic boards and LED spots, of which also need to be carefully assessed. The circular economy approach seems to be more adequate to provide a complete view of the environmental burdens caused by electric and electronic devices starting with identifying and improving the materials used for manufacturing these products and determining their potential replaceability to elongate their useful life.

For this purpose, this paper presents an assessment of conventional LED linear luminaires using Life Cycle Assessment (LCA) methodology, paying particular attention to both Climate Change and Resource Depletion impact categories. The focus of this LCA is to determine the most suitable configurations for LED luminaires to meet industrial lighting regulations with a reduced environmental impact in order to inform design scenarios for Repro-Light. It further assesses the impact of the production of a specific linear LED luminaire in order to identify the components that contribute the most to the selected environmental impacts and that have the potential to be improved through modularity. Results have shown that the electronic components contribute the most to all the selected impact categories. These results are further used to discuss how the circular economy principles can be incorporated in the lighting industry with the objective of reducing the overall environmental impact of LED luminaires across all life cycle stages. Future work will then compare these results to an extensive LCA of the innovative Repro-Light LED luminaire.

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Introduction

Many efforts have been made by the lighting industry to reduce the energy consumption of lighting during the use phase. With the phase out of the incandescent light bulb and the deployment of the Light Emitting Diode (LED), better efficacies have been achieved bringing even further energy savings [1]. Therefore, from an energy efficiency perspective, the potential of LED luminaires is very promising, and the technology has not yet reached its full capability [1]. However, due to the specific material composition of LED luminaires, which consist of electronic boards and LEDs, the environmental benefit of the technology needs to be carefully assessed [2]–[4].

Electronic boards and LEDs consist of elements, such as gallium, aluminium, antimony, gold and copper, to name a few [4]. It is the unsustainable use of these non-renewable elements that could result in adverse environmental and health impacts, including exposure to toxic chemicals. These elements are key components of electronics. In fact, disposal of electronics is a global issue, with only 20% of consumer electronics reported to have been properly disposed of and recycled under appropriate conditions [5]. Directives have been released in order to improve the collection of electronic waste, such as the Waste Electrical and Electronic Equipment (WEEE) Directive, whereby electronic equipment must be collected, sorted and treated separately with the aim of recovering the maximum amount of valuable materials [6]. This includes lighting products, where a recycling rate target of 80% has been set [6].

Although the implementation of policies and directives have led to more lighting products being collected and disposed of properly, the recovery of elements from WEEE in general has been reported to be low dependent on the element to be recovered. For example, gallium which is used in the semiconductor chip in LEDs was recovered at a rate of less than 1% in 2011 [7]. Recycling methods are always improving; however, the recovery process must also be feasible from an economic perspective. By designing products for ease of recycling, as well as improving recycling techniques to obtain higher yields and better quality recovered materials, the economic case for recovery of more elements from electronics may become viable [5]. This, however, may also involve a transformation from the current linear economy to a circular economy.

A circular economy means decoupling prosperity from resource consumption [8]. In a circular economy, economic activity is built for long-term sustainability by not only generating business and economic opportunities, but also providing environmental and social benefits [5], [9]. This economy distinguishes between biological and technical cycles, the technical cycle focusing on reuse, repair, remanufacture, and lastly recycling of products, components and materials [5]. It is this cycle for which improvements in the circularity of electronics and lighting can be made by following the three principles of a circular economy, which are:

1. Designing out waste and pollution
2. Keeping products and materials in use
3. Regenerating natural systems

This circular approach is also useful in providing a complete picture of the environmental burdens caused by electric and electronic devices, starting with identifying and improving the materials used for the manufacturing of these products.

For the lighting industry, the circular economy approach has the potential to lead to benefits for the environment, as well as for the consumer and the economy. By meeting recycling targets and improving the material efficiency and serviceability of lighting products, benefits including a reduction in waste, greater energy savings, longer technical lifetimes, improved luminaire performance due to upgrades, and the creation of jobs and business models all have the potential to be achieved [9].

The work presented in this paper is part of the Repro-Light European project that aims to transform the European lighting industry, making a shift towards circularity. The results of an environmental Life Cycle Assessment (LCA) conducted on conventional LED linear luminaires are presented in this paper with the aim to inform where improvements to the design can be made to reduce the environmental impact across all life cycle stages. LCA is a holistic approach that considers all inputs and outputs throughout all life cycle stages of a product from raw material extraction through to final disposal. The results of the LCA are used to discuss the benefits that can be provided from the modular, customizable, innovative luminaire designed as part of the Repro-Light project and in line with circular economy principles. An extensive LCA will be conducted on the Repro-Light design and compared to the conventional LED luminaire presented in this paper in future work as the project progresses.

Environmental Life Cycle Assessment of Conventional LED Luminaires

This section presents the Life Cycle Assessment (LCA) methodology used for the environmental assessment of the conventional LED luminaires. LCA is divided into four stages including, Goal and Scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and Interpretation. The Goal and Scope define the overall goal of the study, the system boundary, the functional unit, and all other methodological choices required to meet the goal. The functional unit describes the function of the product system being assessed and is the unit for which the data is collected. The LCI is the data collection step, and the LCIA categorizes the LCI data into impact categories defined in the scope, applies the associated characterization model and quantifies the overall environmental impact for each category assessed. The interpretation stage checks that the LCI and LCIA have met the requirements defined in the goal and scope. LCA can be used in comparative studies that assess various design options in an aim to inform where design choices can be used to reduce the overall environmental impact.

For this study, an environmental attributional LCA was conducted to compare the impacts of the production, use and disposal of two lighting systems composed of two different conventional LED luminaires. The LCA is conducted in accordance to the international standards for LCAs, ISO 14040:2006 [10] and 14044:2006 [11]. The two conventional LED luminaires differ in power, and thus material composition and luminous flux. The lighting systems were modelled using Dialux software in order to determine the positioning and the quantity of luminaires required to meet the desired illuminance for the same room dimensions. The scenario chosen for the lighting systems was an industrial hall of 120×60 m that requires an illuminance of 300 lux according to the Technical Rules for Workplaces for Germany [12]. The goal of this study is to determine which of the lighting systems is better from an environmental perspective, one which consists of less luminaires of higher power or one that consists of more luminaires of lower power. This therefore considers the quantity of materials used to produce the luminaires for each lighting system and not only the quantity of energy consumed during the use phase. The study also aims to highlight the components that can be designed for modularity in order to improve the overall impact of lighting systems, thus focusing on reduction in waste generated and materials consumed in new production.

The functional unit of the LCA is defined as an illuminance of 300 lux for a lifespan of 70,000 hours. This is already an improvement of the lifespan of 50,000 hours that has been used in LCA studies for lighting. Other studies have also conducted scenarios for this ranging from 15,000 to 50,000 hours [13]. The lifespan specified

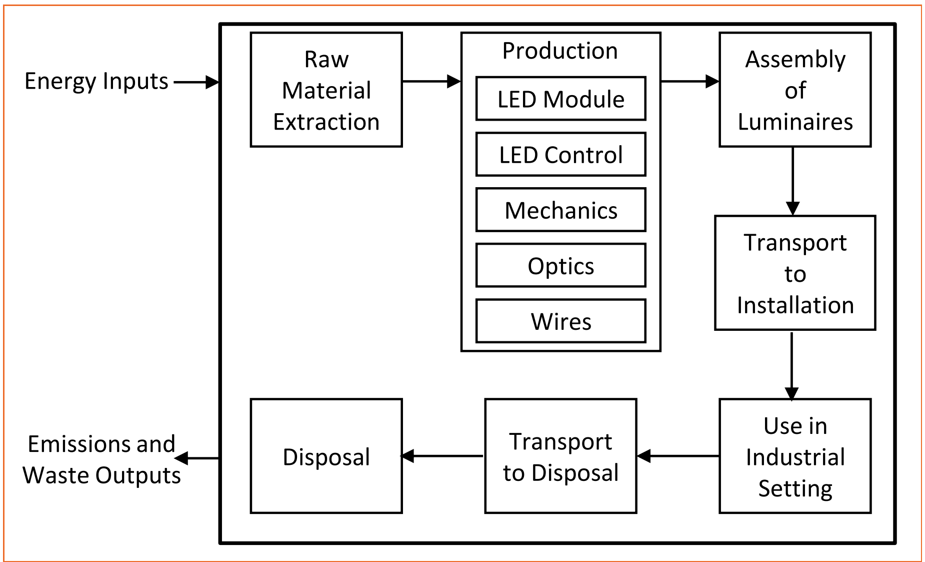

Figure 1: System Boundary for the LCA

for this study was chosen based on the L80 specification for the luminaires, indicating the lifetime at which the LED light output reaches 80% of its initial output. The system boundary defined is shown in **Figure** 1. It should be noted that transportation is only included for transport to installation site and transport to final disposal. The transport to installation is assumed as 30 km and that to the final disposal as 60 km to the waste sorting facility and 80 km from the sorting facility to the treatment facility.

The LCA was modeled using GaBi Professional software, a tool designed for LCA studies assessing a variety of impact categories. Both GaBi 8 Professional and EcoInvent 3.5 datasets were used in the study for the background data. The electricity mix shown in **Figure** 2 is used for this study and corresponds to the EU-28 grid mix. Data for the material composition has come from manufactures of the luminaires, who have also assisted in the selection of the appropriate datasets to use for the background data.

A key limitation for this study is the quality of the datasets available to model the production of the electronic components, such as the LEDs, circuit boards and circuit board components. The datasets are based on average data from average production technologies. Scaling from the functional unit of the dataset to the quantity required per luminaire was done based on linear relationships. For the LEDs, as suggested in the dataset, the scaling was done by mass and volume for one LED. For the other electronic components, such as the components of the circuit board consisting of capacitors, varistor, driver, coils, conductors and transformers, the scaling was done by the only parameter available, the mass per component. The circuit boards were scaled based on the dimensions or mass, according to the functional unit of the dataset used. Improvements in accounting for the limitation in data quality for the electronic components will be assessed in future work. Another limitation of this study is the assumption that the luminaire operates at its full power during its lifetime, however this same assumption has been used for all luminaires compared in the study. Furthermore, the degradation of LEDs has not been considered in the use phase model or the use of functions such as constant light output or daylight control. These are aspects that will be included in future work, along with the dimmability of LEDs during daylight hours in order to reduce the electricity consumed during the use phase. It should also be noted that the energy for assembling the luminaires is based on an estimation from [13], but is to be updated with measured data from the production lines provided by the manufacturer in future work. The results are thus preliminary; however, they are used to inform the design aspects for the Repro-Light luminaire that aims to demonstrate the potential benefits of a modular, serviceable, customizable luminaire design that has the potential to move away from the linear approach of produce, use and dispose.

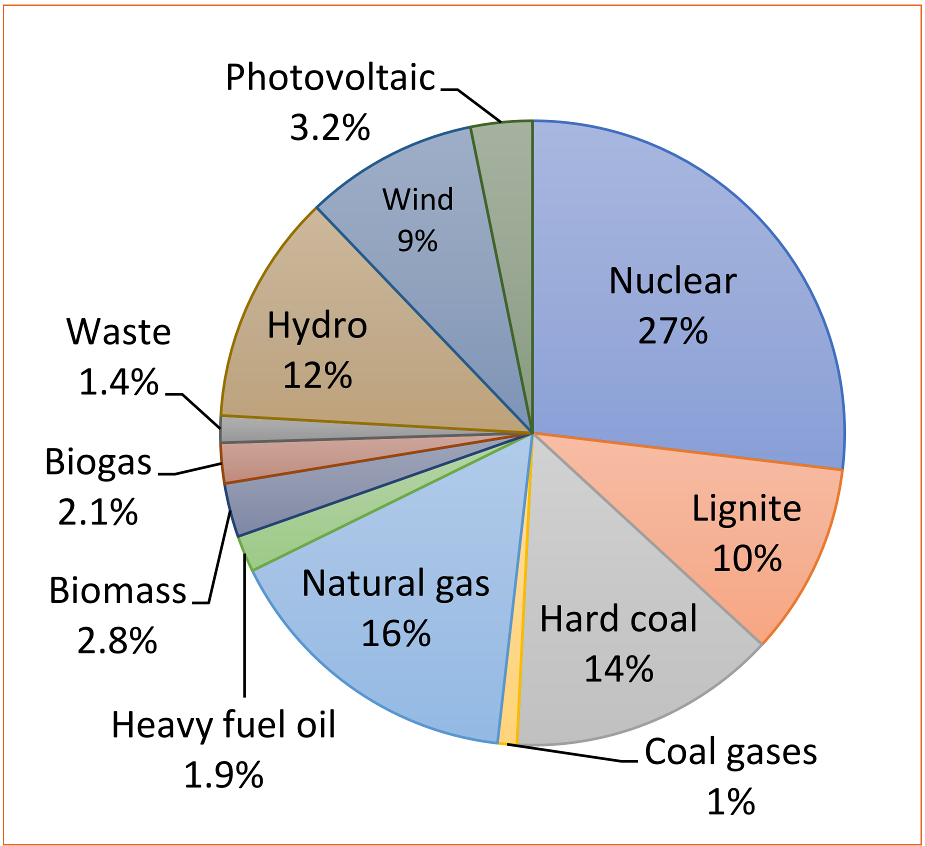

Figure 2: Electricity mix used for the LCA (EU-28 mix). Source: Adapted from GaBi Professional Database

Table 1: Categorization of Luminaire Components

Category	Components
LED Module (LEDM)	Circuit Board LEDs
LED Control (LEDC)	Circuit Board (CB) CB components[1]
Mechanics	Gear Tray Trunking Metal parts Plastic parts
Optics	Optical element End pieces
Wires	Copper Wires

[1] capacitors, varistor, transformers, driver, etc.

Inventory Data for Production of Luminaires

The luminaire was dismantled, and the components were identified and weighted. The components were then categorized into LED Module, LED Control, Mechanics, Optics and Wires, as shown in **Table** 1. Two conventional luminaires were used in this study that differed in power, being a luminaire of 105 W (Luminaire A) and a luminaire of 53 W (Luminaire B). The material composition of both luminaires is the same, except for the material used in the gear tray, being aluminum for Luminaire A and sheet steel for Luminaire B. The energy for manufacturing each component is estimated with that in the background dataset used, and the assembly energy is assumed to be the same for both luminaires, which as stated previously was estimated using data in [13].

Inventory Data for Use and Disposal of Lighting Systems

In comparing the two luminaires, a lighting system was created for an industry hall of 120×60 m using Dialux software. For each lighting system, the illuminance provided was slightly different, therefore it was scaled to the 300 lux requirement for industrial settings [12] in order to allow the results from both lighting systems to be compared. To scale the illuminance to 300 lux, a linear relationship between power and illuminance was assumed, as per discussions with lighting experts. This power was then used to quantify the lifetime energy consumption for the luminaires.

Table 2: Inventory data for use phase for lighting systems

Specification	Lighting System A	Lighting System B
Rated Power	105 W	53 W
Illuminance[1]	327 lux	352 lux
Quantity Luminaires[1]	246	369
Scaled Power	96.3 W	45.2 W
Scaled Illuminance	300 lux	300 lux

[1] Quantified using Dialux software

Data for the disposal of the luminaires was based on the scenario that all luminaires are disposed of properly by being brought to a suitable collection point. Plastic components composed of Acrylonitrile butadiene styrene (ABS) and Polymethyl methacrylate (PMMA) were disposed of by incineration, as well as the electronic components, such as the circuit boards. The recyclable plastics and metals were modelled with open loop recycling without credit. The transport of these products from the collection point to the sorting facility and further to the final recycling facility was included. This model will be updated and improved as better quality data becomes available. Furthermore, scenario analysis for multiple disposal scenarios will be conducted in future work on this model.

Environmental Impact Categories Assessed

Impact categories are used to quantify the potential for specific environmental burdens. For Life Cycle Assessment studies, there are multiple impact categories that can be assessed, as well as multiple models used to quantify the impacts. The impact categories assessed in this study, along with the characterization factors applied and a description of the environmental importance is provided in **Table** 3.

Life Cycle Impact Assessment Results and Interpretation

The Life Cycle Impact Assessment results are presented and discussed in this section. **Figure** 3 shows the total impact from production, use and disposal of one luminaire for all impact categories assessed (as described in **Table** 3). Two luminaires that differ in power and thus luminous flux are shown in the figure to demonstrate the contribution of the production, use and disposal stages to the overall impact for different luminaires. It should be noted, however, that a direct comparison of the two luminaires cannot be made in this figure, as they provide a different quality of light output and thus do not have the same function. The figure shows the use phase energy consumption for both luminaires is responsible for the majority of the total impact for all impact categories, except for ADP Elements. This is in agreement with other LCA studies that found the contribution of the use phase to be greater than 95% for GWP when using the European electricity mix [13], [15]. For ADP elements, the impact due to production of the luminaires is very similar for both luminaires. Therefore, it can be concluded from this figure that in terms of resource depletion of elements due to production of the luminaires, both yield similar impacts. Furthermore, even though Luminaire B emits less energy (has a lower light output) than Luminaire A, the contribution of the use phase is still greater than 95% for both luminaires for all impact categories assessed, except ADP Elements.

In order to compare the use of one luminaire to the other, lighting systems composed of each luminaire were assessed. This comparison ensures the same function is being considered and allows for differences in the environmental impact due to energy consumption and quantity of luminaires to be demonstrated. **Figure** 5 shows the comparison for the lighting scenarios, as were described in **Table** 2, that provide an illuminance of 300 lux to the same industry room.

In **Figure** 5, it can be seen that even with more luminaires required for Lighting System B to meet the defined illuminance, the impact for all categories, except ADP Elements, are lower compared to Lighting System A. For ADP elements, however, the impact due to producing the luminaires is greater for Lighting System B than Lighting System A due to the scenario requiring 123 more luminaires. Yet, the luminaires consume less electricity overall in Lighting System B resulting in a total impact for ADP elements that is very similar to Lighting System A, being 0.48 kg Sb-equivalents for Lighting System A and 0.54 kg Sb-equivalents for Lighting System B. Thus, the savings in materials in one scenario has not significantly outperformed the savings in energy consumption in the other sce-

Impact Category	Characterization Factor	Description
Resource Depletion	Abiotic Depletion Potential Elements (ADP Elements)	The depletion of reserves due to the unsustainable extraction of non-renewable minerals/elements
Resource Depletion	Abiotic Depletion Potential Fossil (ADP Fossil)	The depletion of reserves due to the unsustainable extraction of fossil fuels, including crude oil and natural gas
Acidification	Acidification Potential (AP)	The emission of substances that lead to the change in soil acidity and ecosystem damage
Eutrophication	Eutrophication Potential (EP)	The release of nutrients that lead to growth of algae and cyanobacteria and a relative loss in species diversity
Climate Change	Global Warming Potential (GWP)	The emission of greenhouse gases that lead to increased radiative forcing and raise in mean global temperature
Energy Demand	Primary Energy Demand (PED)	The consumption of both renewable and non-renewable primary energy sources measured prior to processing (net calorific value)

Table 3: Description of Impact Categories Assessed

nario in terms of extraction of elements. However, it is important to note here that this is the situation for the electricity mix that was used in the study. As the gird mix changes, differences in the results will occur as has also been indicated in [13], [15].

Although the electricity mix used is a significant factor for the results generated, the trends in the variation of ADP elements and GWP with the hours of use for the Lighting Systems were explored further. These trends are shown in **Figure** 4 and **Figure** 6. In both figures, the intercept is the impact due to production and disposal of the luminaires in the lighting systems. The slope of the line is thus the impact per hour use that comes from the impact for production of electricity per kWh, steeper slopes indicating a higher electricity consumption per hour. **Figure** 4 shows that with longer lifetimes, the impacts become more similar for both lighting systems using the EU-28 grid mix. However, the opposite trend is seen for GWP, and will be seen across all other impact categories where the use phase is contributing to the majority of the impact. These two figures illustrate further the importance considering multiple impact categories when conducting environmental assessments, as improvement in one impact category can lead to reverse impacts in another.

With the integration of more renewables on the grid as well as with further improvements in the energy efficiency of LED luminaires, the materials may become even more significant in their contribution to the overall environmental impact. Because of this, the contribution of the components to the production phase for the luminaires in the lighting systems was further investigated. **Figure** 7 shows the contribution of each component to the total result due to production. The breakdown of the material categories is given in Table 1.

From **Figure** 7, the LEDM and LEDC contribute significantly to the overall ADP Elements for production. These components consist of electronic components that were assumed to be the same for both Luminaire A and Luminaire B. However, as previously stated the quality of the data for these electronic components needs further assessment. At the time of the study, the data used was considered to be the best available.

It can further be noted from these results that in terms of luminaire design, the reduction of electronic components will lead to a reduction in the environmental impact.

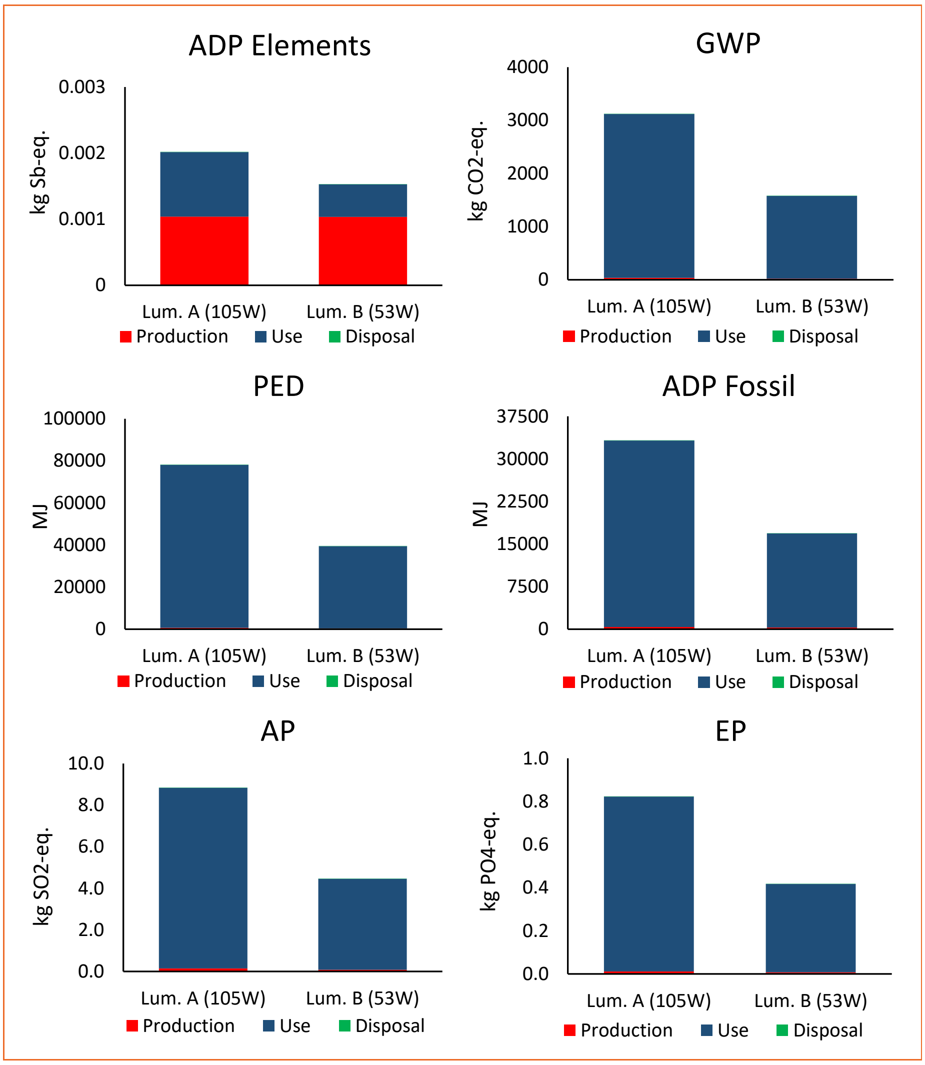

Figure 3: Contribution of Production, Use and Disposal life cycle stages to the overall impact for two single luminaires providing different luminous flux

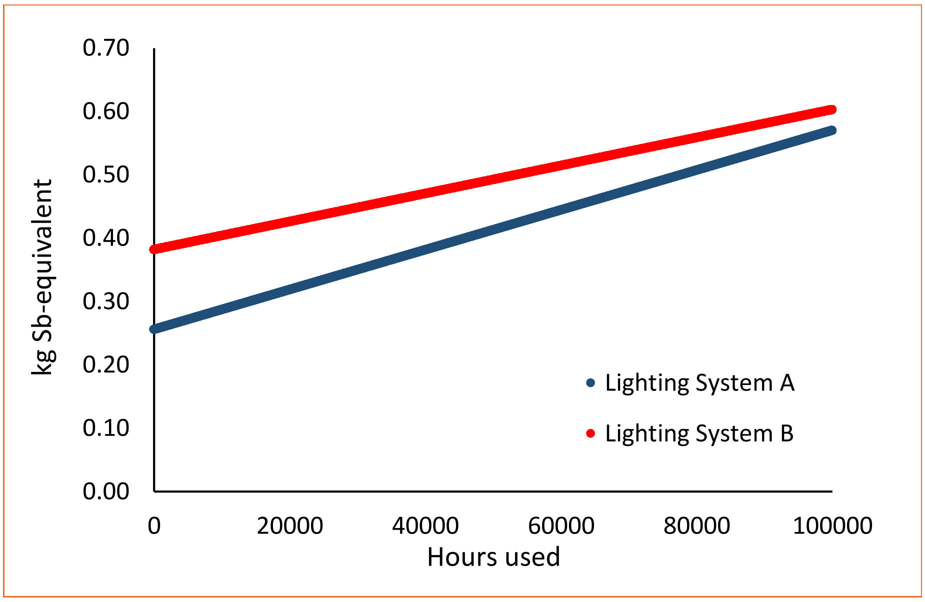

Figure 4: Variation of total ADP elements with hours of use for Lighting System A versus Lighting System B

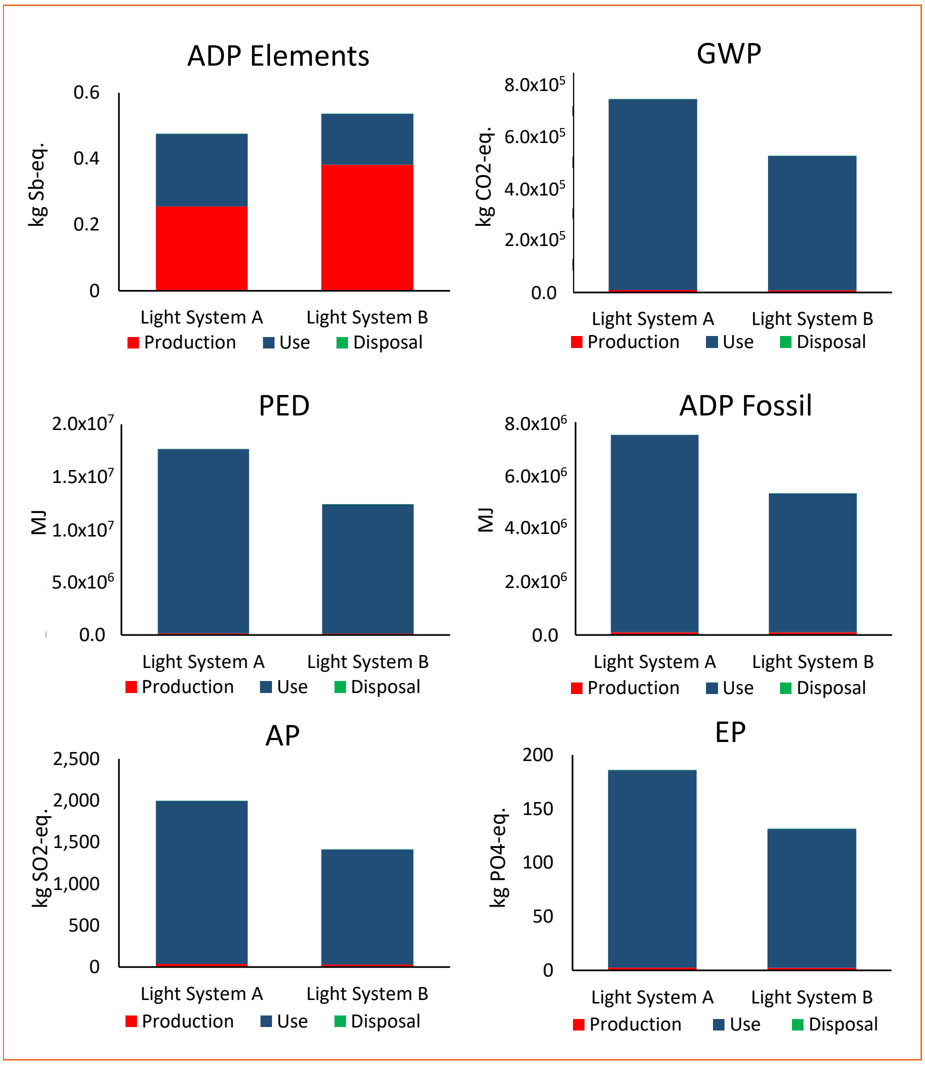

Figure 5: Comparison of two lighting systems configured with luminaires from Figure 3 that provide the same illuminance in an industrial setting. The contribution from Production, Use and Disposal is also shown

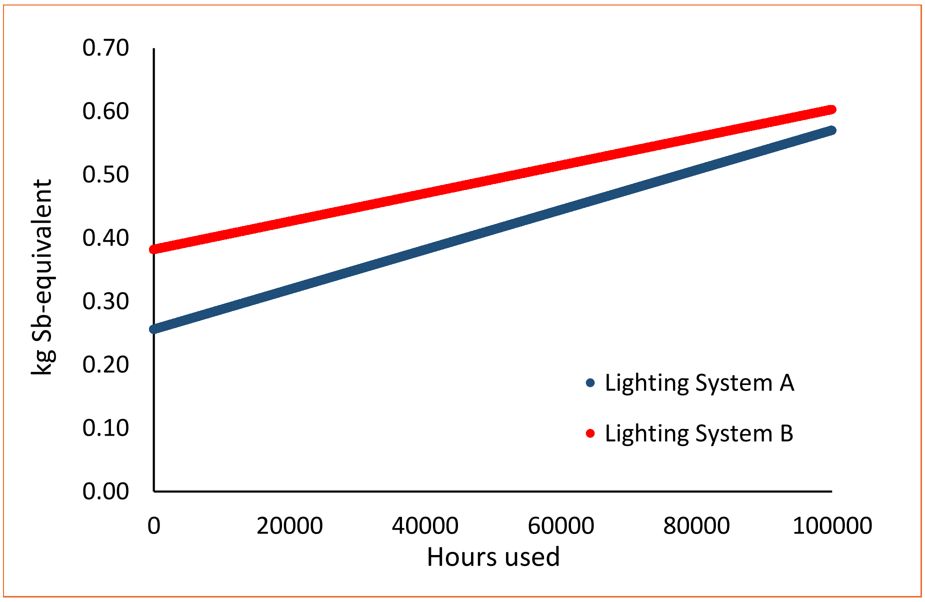

Figure 6: Variation of total GWP with hours of use for Lighting System A versus Lighting System B

For example, reductions can be made for the size of the circuit boards in the LEDM and LEDC, as well as in the number of components on the circuit board. Both aspects are being considered in the Repro-Light luminaire, to ensure a more efficient use of materials. The LEDC and LEDM are also potential components for modularity, allowing for replacement of the parts as opposed to disposal of the entire luminaire and leading to reductions in waste generation as well as material use by keeping parts of the luminaire in use for longer. These components are being designed for modularity within the Repro-Light project.

Concluding Remarks

The European lighting industry can move towards a more sustainable future by incorporating the circular economy principles in the design of lighting. To do this, luminaires should be modular and serviceable, which in turn will allow for the creation of business models and new job opportunities. Furthermore, reductions in waste generation and material consumption are obtainable with the ability to replace parts. Therefore, benefits will not only be made from an environmental perspective, but also economic and social.

As was seen in the results from the LCA, the components of the LED luminaires that contribute the most to the environmental impact from production are the electronic components. Therefore, the design of modular LEDM and LEDC components with better material efficiency, such as optimizing the size of circuit boards and the quantity of circuit board components and LEDs can lead to reductions in the environmental impact from these components. Furthermore, the industry can look at second life options for old LEDs once they have reached the end of their first life, being once the light output has reduced to 80% of the initial value. These LEDs can be repurposed to other applications, such as emergency lighting, and thus keep the materials in use for longer. Recycling technologies are also improving to extract the elements from electronics products at the end of its useful life, which can help to further reduce the impact from resource depletion of non-renewable elements.

The Repro-Light project aims to initiate a change the European lighting industry, seeking for better design aspects not only for the consumer but also for the environment and the economy. Further work will be conducted to compare the Repro-Light design to the conventional in order to carefully assess the product innovations. An

LCA of the use of the Repro-Light luminaires in the same industrial setting will be conducted, considering the degradation of the LEDs, the reduced power consumption due to dimming the lighting when combined with natural light, variation in the dimensions of the LEDC and LEDM circuit boards, and the addition of other electric components, such as sensors, that will enable the functionality of the luminaire. The LED has yet to reach its full potential in achieving even more energy savings in the use phase and is thus a promising technology for leading the way to incorporating circularity of products in the European lighting industry. ■

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The **Catalonia Institute for Energy Research (IREC)** was founded to contribute to more sustainable energy use and consumption in the future. Economic competitiveness and maximum energy security are both taken into consideration. IREC makes its contribution through advances in science and technology.

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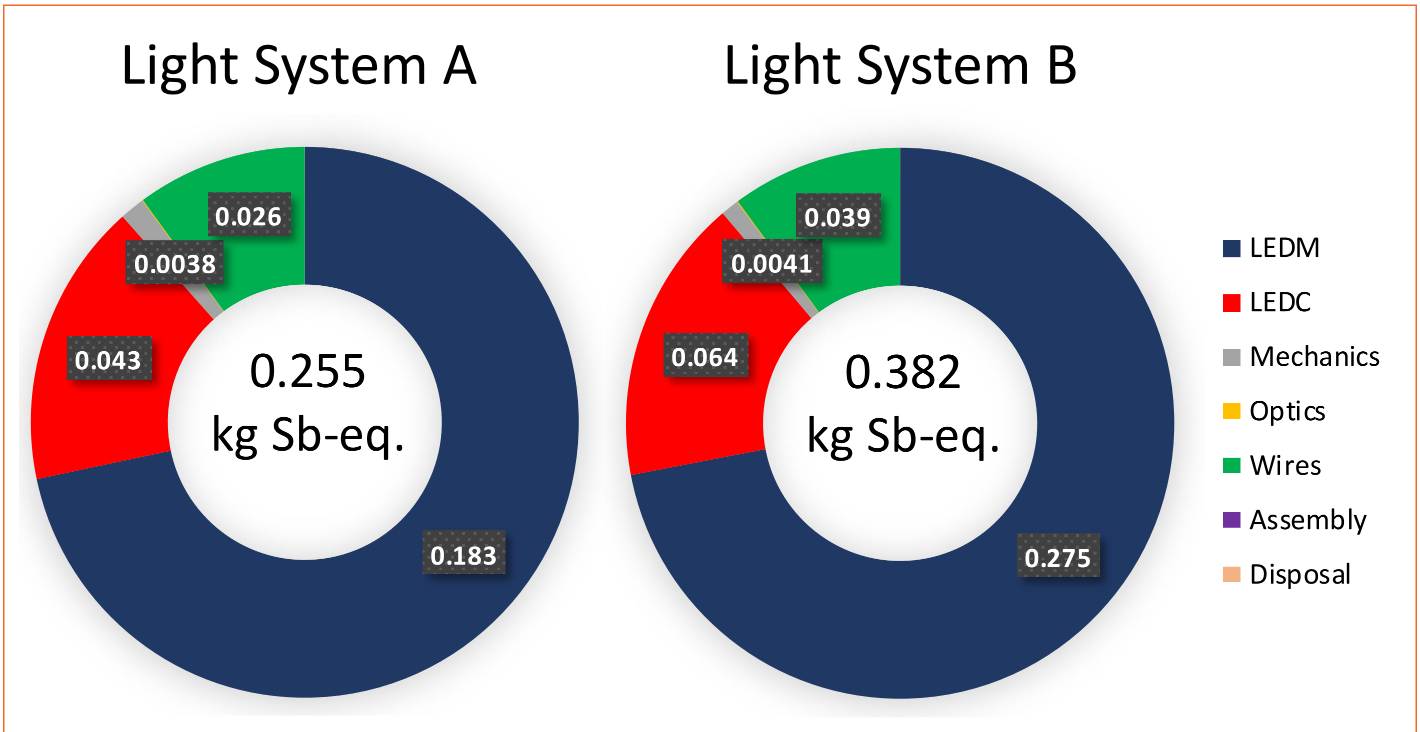

Figure 7: Contribution of components of the luminaires to the overall impact for production of Lighting System A and Lighting System B

International Solid State Lighting Alliance (ISA)

International SSL Alliance

Who we are?

ISA is a non-for-profit organization consists of regional alliances, association/society, leading companies and renowned universities in global Solid State Lighting (SSL) field.

The Business of ISA members have covered the whole SSL value chain of upstream, middlestream and downstream of global SSL industry such as epitaxy, packaging application, materials and equipment, design system integration and testing etc.

Currently, ISA has 82 members, representing more than 4000 individuals & organizations includes major players (such as Philips, Osram, Smsung, GE Lighting, Cree, Veeco, AIXTRON etc.). The output of which covers more than 70% that of global SSL industry.

The ISA Board of Advisers consists of leading experts and academic “Founder” level experts, such as the inventors of blue LED, yellow LED, Red LED, and OLED. Amongst Professor Shuji Nakamura, the Laureate of Nobel Prize in Physics in 2014 is the Co-Chair of ISA Board of Advisors (BOA) and Professor Hiroshi Amano the Laureate of the Nobel Prize in Physics in 2014 is the member of ISA BOA. The current president of ISA is Dr. Jianlin Cao, the former vice minister of Ministry of Science and Technology, China.

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- ISA-ECC Smart Street Lighting System Specialized Committee
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EU's Ecodesign and Energy Labelling Regulations

In December 2019, the European Commission published the new Single Lighting Regulation (SLR) (i.e. Ecodesign Regulation for lighting) and the Energy Labelling Regulation (ELR). Whereas the SLR sets product-specific performance requirements for energy-using and energy-related products, the ELR lists the labelling requirements for selling those products on the EU market.

The result of nearly five years of negotiations, the SLR and ELR will apply from 1 September 2021, except for the removal of labelling requirements for luminaires starting from 25 December 2019. Both will have significant consequences for the lighting industry. ELR applies to light sources only, while SLR applies to light sources and separate control gear, with luminaires only being indirectly addressed. Nevertheless, luminaire manufacturers must review the rules and ensure that their products comply with the new requirements. To ensure you have all the information you need to comply with these complex regulations, LightingEurope has put together the following summary.

Ecodesign – Improving Product Performance

The Ecodesign Regulation (SLR) establishes EU-wide rules for improving product performance, including that of lighting. It pertains to light sources and separate control gear and to light sources and separate control gears within a containing product.

Similar to the ELR, the SLR defines a light source to include lamps, modules, and even some containing products. A containing product is defined as a product containing one or more light source(s), or separate control gears, or both. Examples of containing products are luminaires that can be taken apart to allow separate verification of the contained light source(s), household appliances containing light source(s) and furniture (shelves, mirrors, display cabinets) containing light source(s). According to the SLR, the supplier of a containing product must ensure that the light source and separate control gear used in their containing product complies with all relevant EU legislation – including the SLR.

As the SLR sets minimum mandatory requirements for energy efficiency, any product that fails to meet these requirements will be phased out, starting with products like CFLi lamps in 2021 and followed by products like T8 fluorescent lamps in 2023. As this phase-out happens, these light sources will need to be replaced with new energy-efficient light sources and lighting installations will have to be renovated.

The new SLR introduces several elements of the circular economy. For example, manufacturers, importers, and authorised representatives of containing products must ensure that light sources and separate control gears can be easily replaced using commonly available tools and without permanently damaging the containing product. Furthermore, they need to provide instructions on how to 'extract' a light source, which can be explained using drawings, text, images, etc. If a technical justification related to the functioning of the containing product is provided in the technical documentation explaining why the removal for verification of light sources and separate control gear is not appropriate, then the entire (containing) product has to satisfy all the performance/information requirements.

The SLR also requires that manufacturers, importers, and authorised representatives of containing products provide information about the replaceability or non-replaceability of light sources and control gears by end-users or qualified persons. This information must be made available on both the packaging and in the user instructions, typically in the form of a pictogram. However, these symbols are not to be used on containing products that are a light source (e.g., luminaires). For your convenience, LightingEurope has developed pictograms covering the required information on replaceability/non-replaceability, which are included in guidelines (details at end of article).

Summarising the SLR

- All containing products must have replaceable light sources and control gear (unless there is a technical explanation for not doing so).
- If the light source and control gear of the containing product cannot be removed for verification, then the containing product is considered a light source for all requirements of the SLR (energy performance requirements, information requirements, etc.) and the corresponding energy labelling requirements.
- Information on the replaceability or non-replaceability of the light source and the control gear must be displayed on the packaging of the containing product (only for products sold directly to end-users).

ELR – Empowerment through Information

The ELR pertains to light sources, which includes lamps, modules, and even some containing products (there is no energy label requirement for luminaires) and requires manufacturers to provide more information about its energy performance and functional parameters.

One of the ELR's main objectives is to empower the customer/end user by giving them the information they need to choose energy efficient products. Thus, first and foremost, the Regulation requires that specific product information be provided via a consumer-friendly energy label. The ELR also requires that the manufacturer provide information on the product's class, along with other relevant technical information.

As the Regulation applies to the entire supply chain, there are different requirements for what information must be provided by whom. For example, suppliers (i.e., manufacturers, authorised representatives, and importers) must place an energy label on the packaging of all independently packaged light sources. Furthermore, upon the request of a dealer, the supplier has to provide a printed version of the product information sheet (the information must always be available electronically).

Dealers (i.e., retailers), on the other hand, must follow their own set of requirements. For instance, the energy label needs to be visibly displayed on a light source's packaging and, in the case of distant selling, the label and product information sheet must also be provided. Advertisements promoting a product have to include not only that product's energy efficiency class, but also the range of energy efficiency classes listed on the label.

The Regulation also includes specific obligations for online retailers and hosting platforms. For example, online retailers must include the energy label and the product information sheet on the website where the light source is sold.

By specifying the size that an energy label must be (72×36 mm or 54×20 mm), the ELR also regulates the minimum size that a package can be (i.e., no smaller than 54×20 mm). All labels created based on the old regulation must be replaced with new labels before 1 March 2023. If one intends to cover an old label with a new label, one must ensure that the new label completely covers the old label. (Note: energy labels are no longer required for luminaire packaging).

In addition to the labels themselves, the ELR requires that all the information included on a product's energy label and in its technical documentation also be entered into the European Product Database for Energy Labelling (EPREL). As is the case with the label and documentation themselves, entering the required data into the EPREL is a prerequisite for selling a product on the European market. Already since 1 January 2019, registration of lamps in EPREL 1.0 and providing product information is already mandatory. The requirement of an energy label on luminaires has been withdrawn as of 25 December 2019.

However, although the details are not yet entirely clear, as of 1 September 2021, the EPREL 2.0 will also be mandatory for light sources and containing products considered to be a light source.

Consequences following the SLR

- Phase-out of some conventional lighting technologies due to increased efficiency requirements on performance and quality of light
- Removability and replaceability requirements for light sources and control gears in containing products

Consequences following the ELR

- All light sources in scope of the SLR are also in the scope of the ELR
- Discontinuation of energy labelling for luminaires (containing products must be labelled only if they are a 'light source')
- New information obligations through EPREL

The Voice of the Lighting Industry

As the voice of the lighting industry, LightingEurope is dedicated to helping companies understand and apply these complex new rules. That is why we developed and published a set of detailed Guidelines on both the SLR and ELR, which anyone can download for free at: https://europeanlightingpriorities.eu/guidelines.php

LightingEurope has also produced guidelines for existing EPREL requirements, which we made available to our members. New guidelines for the next set of requirements applicable from 1 September 2021 are planned.

To learn more about how LightingEurope can help you navigate regulatory changes and ensure you have the information you need to make informed investment decisions, visit us at www.lightingeurope.com The content of the Guidelines is the interpretation of Regulations (EU) No 2019/2015 and 2019/2020 as understood by the members of LightingEurope and by no means represents an official interpretation of the requirements set by the Regulations themselves. While we have made every attempt to ensure that the information has been obtained from reliable sources, LightingEurope is not responsible for any errors or omissions, or for the results obtained from the use of this information. ■

Specifying LED Colors for Horticultural Lighting

Whereas human vision relies on five opsins as photoreceptors, most plants have a wide variety of photopigments that are responsive to optical radiation from 280–800 nm. Beyond photosynthesis, plants rely on this radiation to control photomorphogenesis, phototropism, shade avoidance, and both circadian and circannual rhythm entrainment. Ian Ashdown, Senior Scientist at SunTracker Technologies proposes an LED "color" specification that represents a given SPD using a small number of radial basis functions that provides a metric for comparing biologically similar SPDs. He further introduces a trainable fuzzy logic SPD classifier that can compare biologically similar SPDs for specific horticultural applications.

Quasimonochromatic LEDs have proven a boon for botanists in that the molecular genetics of these responses can be elucidated with precisely-controlled Spectral Power Distributions (SPDs). In terms of photopigments, cryptochromes for example respond to blue light, while phytochrome responds to the R:FR ratio of red (≈660 nm) to far-red (≈735 nm) light. The problem is that botanists do not define what is meant by "blue," "green," "yellow," "red," and "far-red" visible light, while ultraviolet radiation is broadly defined as UV-A and UV-B. Consequently, it is difficult to replicate laboratory experiments without knowing the SPD of the horticultural light source.

Introduction

When the first high-pressure sodium (HPS) lamps were introduced in the late 1960s, they were quickly adopted by commercial greenhouse operators as a means of providing supplemental electric lighting. This made it economically possible to grow vegetables and flowers throughout the year in controlled environments. They had luminous efficacies ranging from 100–150 lm/W, they were available in sizes ranging from 400–1000 W, and they could be incorporated in luminaire housings designed to withstand the heat and humidity of greenhouses.

One disadvantage of HPS lamps is they produce mostly yellow light with fixed spectral power distributions (SPDs). This is not particularly important for plant photosynthesis, as most plants can take advantage of optical radiation within the spectral range of 400–700 nm. Horticulturalists often refer to the "McCree curve," which plots average photosynthesis efficiency versus wavelength for a variety of field-grown crops [1]. As shown in **Figure** 1, the spectral output of HPS lamps is near the peak of the McCree curve.

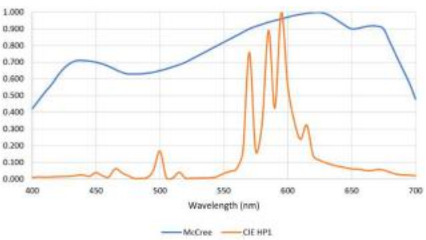

Figure 1: Typical HPS lamp spectral power distribution versus McCree curve [1]

The problem is that while the yellow light of HPS lamps may be good for photosynthesis, plants have a wide range of photopigments that respond to optical radiation from 280–800 nm (often referred to as photobiologically active radiation," or PBAR).

The responses to optical radiation include:

- Photomorphogenesis – any change in the morphology (i.e., shape) or composition of a plant or its components that is induced by optical radiation exposure.
- Photoperiodism – response of a plant to daily (circadian) or seasonal (circannual) changes in optical radiation exposure.
- Photosynthesis – conversion of "photosynthetically active radiation" (PAR) into chemical energy stored as carbohydrates to fuel plant activities.
- Phototropism – any self-actuated change in the orientation of a plant or its components towards or away from optical radiation.
- Secondary metabolite production – organic compounds not directly involved in plant growth, development, or reproduction, including compounds used as medicines, flavorings, pigments and drugs.
- Shade avoidance – a set of responses to being shaded by other plants, including changes in morphology, flowering times, and allocation of resources.

While many of these responses have been known or suspected for decades, it was difficult for botanists to study them in the laboratory without suitable light sources. This changed, however, with the introduction of horticultural luminaires with high-flux quasimonochromatic light-emitting diodes (LEDs). Somewhat serendipitously, the absorption spectra of chlorophyll A and B have peaks that correspond with those of ≈450 nm InGaN and ≈660 nm AlInGaP LEDs (**Figure** 2). Today, the photon efficacy (measured in micromoles of PAR photons per Joule rather than lumens) of LED modules is typically greater than equivalent 1000-watt HPS lamps.

Wavelength Range	Color Name	Photopigments	Responses
280–315 nm	UV-B	UVR-8	Secondary metabolism, Shade avoidance, Phototropism
315–400 nm	UV-A	Chlorophylls, Cryptochromes, Phototropin, Phytochromes, Zeitlupe family	Secondary metabolism, Photomorphogenesis
400–500 nm	Blue	Carotenes, Chlorophylls, Cryptochromes, Phytochromes, Zeitlupe family	Photosynthesis, Secondary metabolism, Shade avoidance, Phototropism, Photoperiodism
500–575 nm	Green	Cryptochromes	Photosynthesis, Secondary metabolism, Shade avoidance
575–610 nm	Yellow / Orange	<Unknown>	Photosynthesis, Secondary metabolism
610–700 nm	Red	Chlorophylls, Phytochromes	Photosynthesis, Photomorphogenesis, Secondary metabolism, Shade avoidance, Photoperiodism
700–800 nm	Far-Red	Phytochromes	Photo-morphogenesis, Shade avoidance, Photoperiodism

Table 1: Plant responses to optical radiation

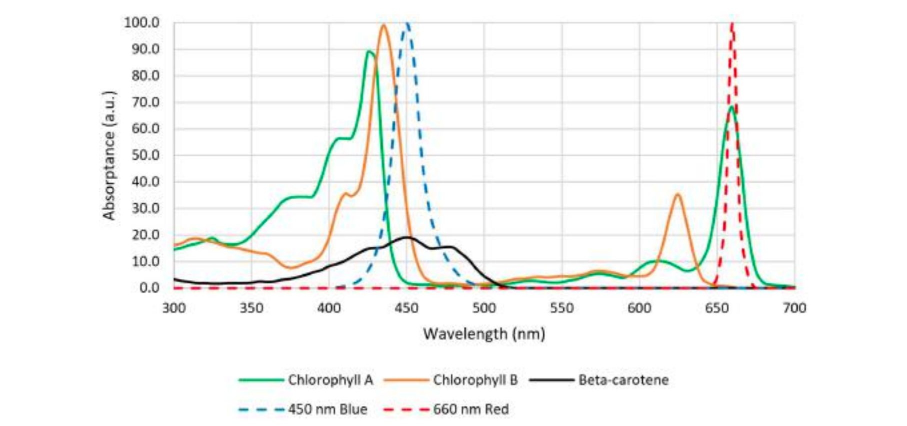

Figure 2: Chlorophyll and β-carotene absorption spectra

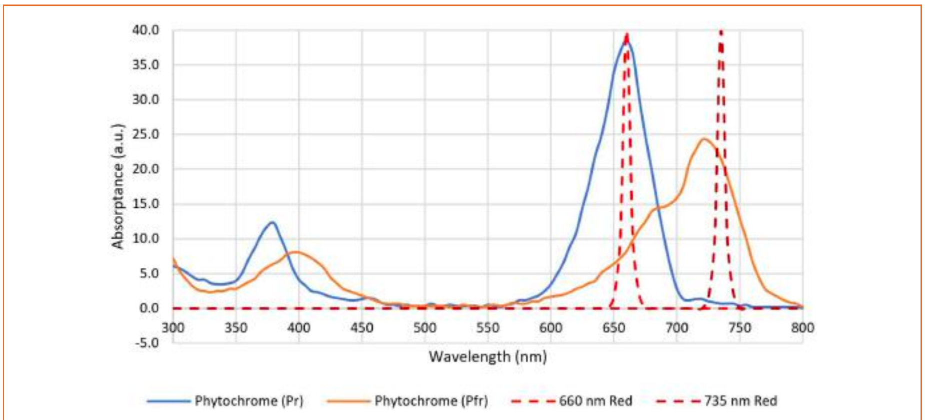

Figure 3: Phytochrome absorption spectra

While commercially available horticultural luminaires with blue and red LEDs (producing so-called "blurple" light) are now successfully competing with traditional HPS luminaires, botanists' attention has turned to the capabilities of multichannel LED luminaires with controllable SPDs. Over 500 academic studies over the past decade have investigated the effects of different wavelength ranges on plants and their absorption by photopigments (**Table** 1).

The problem is that while UV-A and UV-B are formally defined in the scientific literature [2] the visible color names are colloquial and based on human visual responses. The title of one paper in particular illustrates this issue: "Green Light Drives Leaf Photosynthesis More Efficiently than Red Light in Strong White Light: Revisiting the Enigmatic Question of Why Leaves are Green" [3] For anyone interested in either replicating the experiments or extrapolating their results, what are "green," "red," and "white" light?

The color name "far-red," which refers to the spectral range of 700–800 nm, is formally defined in terms of horticulture [4]. It is important in terms of shade avoidance and photoperiodism, where plants rely on two isoforms of phytochrome to detect the ratio of red to far-red (R:FR) optical radiation [5], but there is no equivalent definition of "red" (**Figure** 3).

Luminaire manufacturers are now offering products with 660 nm red and 735 nm far-red LEDs to induce or delay flowering in ornamental plants [6], but many previous horticultural studies have relied on daylight alone or daylight and incandescent lamps to explore the effects of varying R:FR. How should these studies be interpreted in terms of modern horticultural lighting practices with LED-based luminaires?

Characterizing SPDs

Horticultural researchers have recognized that the use of colloquial color names is a problem. Many papers describe their experimental methods in detail, including light source SPD plots, names of specific luminaire products, and occasionally tabulated SPDs. This still leaves open, however, the problem of interpreting the results in terms of other optical radiation sources with similar SPDs. One proposed product label for horticultural light sources is shown in **Figure** 4 [7].

By avoiding the use of color names, this proposal eliminates any dependence on the human visual system. However, the arbitrary separation of the PBAR spectral range into 100 nm wide bands ignores the distinct responses of plants to UV-A and UV-B radiation, and also the response of plants to narrower changes in wavelength.

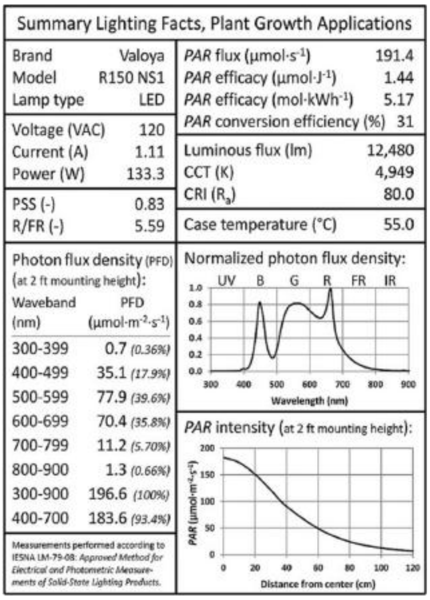

Figure 4: Proposed Product Label for Electric Lamps Used in the Plant Sciences (Image Credit: Both, A.-J., et al. 2017 [7])

For example, Johkan et al. [8] provide an example wherein the growth of lettuce under quasimonochromatic radiation from "green" LEDs with center wavelengths of 510 nm, 520 nm, and 530 nm varies markedly depending on the center wavelength for the same photosynthetic photon flux density (**Figure** 5).

The spectral absorptance characteristics of the primary plant photopigments chlorophyll A and B, β-carotene, and phytochrome (**Figure** 2) suggest that their absorptances vary very rapidly with changes in wavelength. However, these data represent the spectral absorptance of the pigment extracts dissolved in solvents (i.e., in vitro). As shown by Moss and Lewis [9], a combination of the structural complexity of the leaves, screening by other photopigments, and the presence of accessory photopigments have the effect of broadening the spectral absorptance characteristics of the photopigments in vivo. Studies such as those of McCree [1] have shown that in general, plants are reasonably tolerant of small changes in the center wavelengths of quasimonochromatic radiation. (Johkan et al. 2012 [8] was likely an exception in that photosynthesis probably occurred due to β-carotene rather than chlorophyll A/B, with longer wavelengths of green light being incapable of exciting this photopigment.)

In view of this and other studies, it is clear that any attempt to characterize the SPDs of horticultural luminaires needs to take into consideration the responses of plants to changes in center wavelength of quasimonochromatic light sources, and more generally to horticultural luminaires with both quasimonochromatic and broadband radiation sources.

In relation to this, Maloney [10] discusses the physical basis of spectral reflectance distributions from natural objects, including organic materials. These distributions are band-limited by molecular interactions and superimposed vibrational and rotational patterns, with the result that the number of parameters needed to adequately represent spectral reflectance distributions in visible light (i.e., 400–700 nm) is five to seven. Westland et al. [11] came to a similar conclusion based on statistical studies of reflectance spectra, noting that the spectral reflectance distributions of most natural surfaces form a set of band-limited functions with a frequency limit of approximately 0.02 cycles per nm. This implies that the visible light reflectance spectra can be adequately represented using six to twelve basis functions [12].

A small number of radial basis functions [13] can therefore be used to approximate a real-valued function (such as an SPD) as a weighted sum of the basis functions. As an example, the set of Gaussian functions can be used to approximate any SPD from 350–800 nm, where the functions are separated by 25 nm (**Figure** 6):

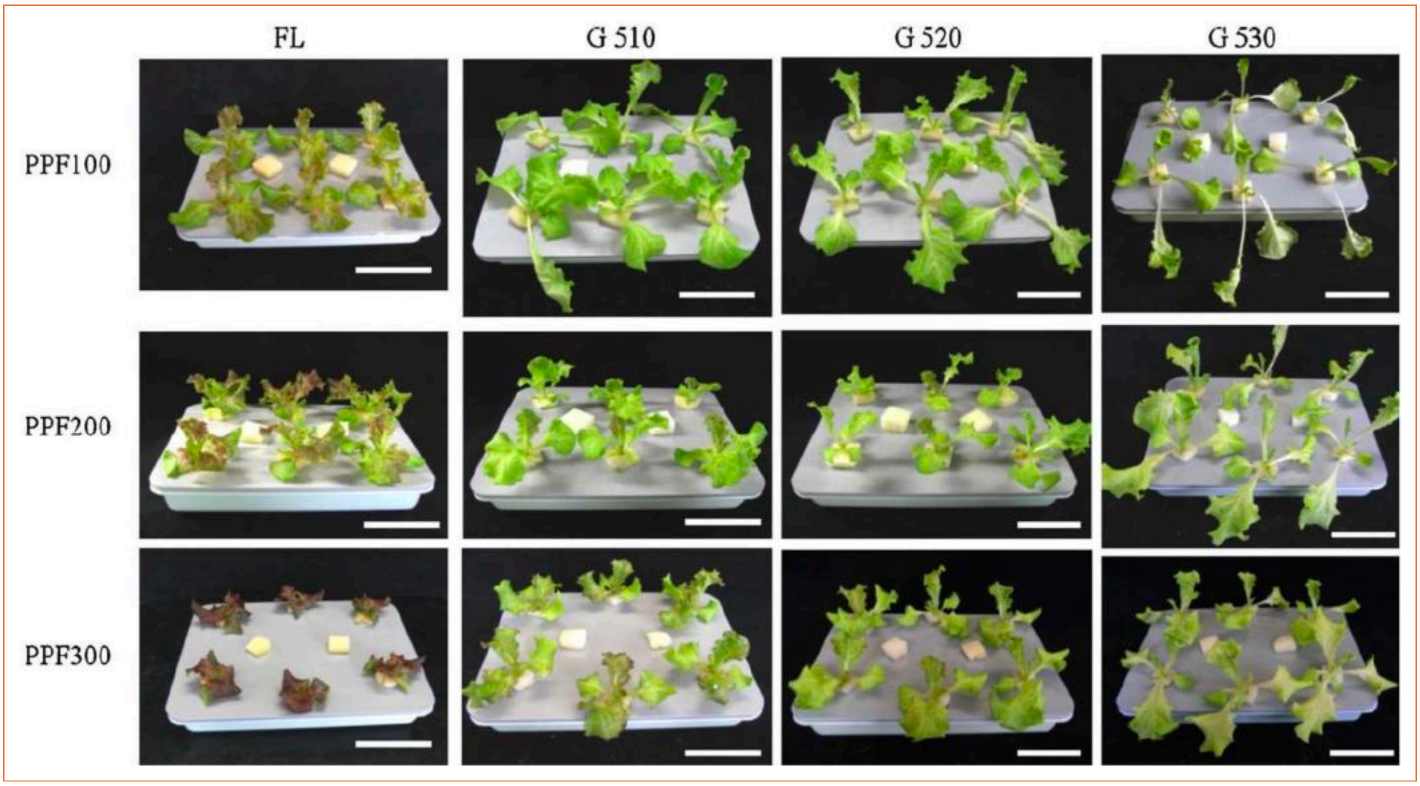

Figure 5: Effect of Green Light Wavelength and Intensity on Photomorphogenesis and Photosynthesis in Lactuca sativa (Image Credit: Johkan, M. et al. 2012., [8])

$$\varphi(r, x_i) = e^{-((r-x_i)/\varepsilon)^2} \qquad (1)$$

where

$$\varepsilon = \sqrt{-\ln(1/\sqrt{2})} = 21.233$$
$$x_i = 350 + 25i \text{ for } i = 0, \ldots, 18$$

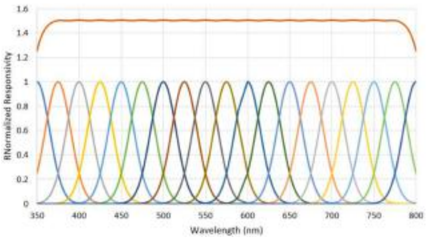

Figure 6: Sum of Gaussian radial basis functions provide flat spectral sensor response

An advantage of this method is that the set of basis function weights is much smaller than the set of enumerated values for a measured SPD. Rather than referring to "red," "green," "blue," or "white" light, horticulturalists can state the values of a set of basis function weights. Moreover, a useful approximation of the original SPD significant to the needs of horticultural lighting can be reconstructed from these weights.

As an example, **Figure** 7 shows 13 radial basis functions over the visible light range of 400–700 nm that are each multiplied on a per-wavelength basis by the SPD of a 4000 K white light LED to yield the basis function weights.

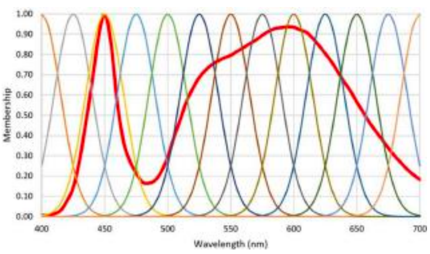

Figure 7: Radial basis function weights for a 4000 K white LED SPD

Figure 8 shows a reconstruction of the LED SPD using a cubic spline curve with the weights as knots. The reconstruction is clearly different from the original SPD, but in terms of predicting plant responses, it is likely adequate.

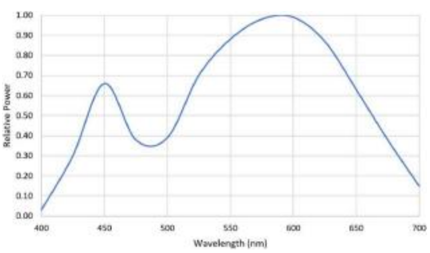

Figure 8: Spline reconstruction of 4000 K white LED SPD from radial basis function weights

Horticultural Spectral Sensor

Referring to **Figure** 6, each basis function can be seen as the responsivity of a radiant flux meter in combination with a Gaussian bandpass filter with a center wavelength of xi. Combining the unweighted outputs of the 19 filtered meters results in a flat response from 375–775 nm. Presented with an arbitrary SPD, the filtered meter outputs represent the appropriate weighting for the basis functions to approximate the SPD. Moreover, the absolute values of the filtered meter outputs can be used to estimate the absolute spectral irradiance incident on the meters, from which can be calculated the absolute irradiance in watts per square meter and the photosynthetic photon flux density (PPFD) in micromoles per square meter per second.

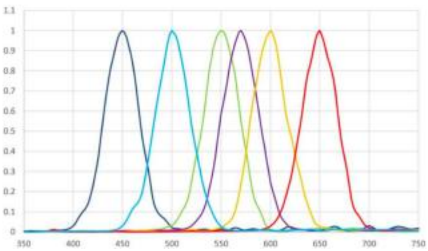
Figure 9: Spectral responsivity of ams AS7262 6-channel visible light spectral sensor

Figure 9 shows the spectral responsivities of an AS7262 6-channel visible light spectral sensor with a spectral range of approximately 430–570 nm, as manufactured by ams AG of Premstaetten, Austria. While the spectral responsivities are not ideal Gaussian functions, it is clear that an instrument to directly measure radial basis function weights can be fabricated using existing technology.

An advantage of this system and method in terms of horticultural light sources is that the spectral power distributions can be unambiguously measured and expressed as a small set of numbers, regardless of the SPD complexity. If the representations of two SPDs are similar, the horticulturalist may be assured that they will likely have the same biological effect on a plant species. As an example, white light fluorescent lamps typically exhibit a combination of continuum and line spectra, whereas white light LEDs typically exhibit a narrow peak emission near 450 nm and a broad continuum from the blends of green- and red-emitting phosphors (**Figure** 7). Regardless, if their sets of radial basis function weights are similar, the two light sources may also be regarded as similar with respect to horticultural applications.

Fuzzy Logic SPD Classifier

The unanswered question is, what does "similar" mean in the context of comparing two or more SPD representations? With 13 to 19 radial basis function weights as parameters, it becomes impractical to formulate a table of rules for comparison purposes. The solution to this problem is a fuzzy logic classifier.

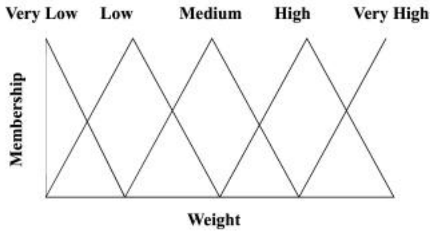

Figure 10: Fuzzy set with five triangular membership functions

Fuzzy logic is often seen as a mathematical means of representing vagueness and imprecise information when making decisions, where input signals are "fuzzified" by mapping their precise values to a set of fuzzy membership functions. Referring to **Figure** 10 as an example, a radial basis function with weight 0.85 has membership 0.60 in "high" and membership 0.40 in "very high." (Triangular membership functions are used in this example, but trapezoidal and sigmoid functions may also be used.)

Referring to **Figure** 7, the fuzzification of the set of 13 radial basis function weights results in **Table** 2:

The set of n fuzzified weights for a given SPD is then submitted to a fuzzy if-then rule system. Given any two fuzzified weights x_1 and x_2 as inputs, a typical fuzzy rule will be:

IF x_1 is low AND x_2 is high $THEN$ output class is Y where there are multiple output classes.

Each rule calculates a "vote" τ that is determined by degree of membership μ for each fuzzified weight:

$$\tau(x_1, x_2) = \mu_{\text{low}}(x_1) \; AND \; \mu_{\text{high}}(x_2) \qquad (2)$$

and where the fuzzy AND operator is implemented as the minimum of the two membership values. Once all of the rules have been processed, their votes are aggregated:

$$\text{output class} = \max(\tau_i, (x_j, x_k)) \qquad (3)$$

for all votes.

This is arguably the simplest possible implementation of a fuzzy logic classifier. There are other methods for calculating and aggregating votes that are likely better for the purpose, but it is the principle that is of interest. What a fuzzy logic classifier accomplishes is a framework for representing expert knowledge of the effect of similar but different SPDs on plant growth and health, taking into consideration the plant species, plant growth stage, plant environmental conditions, and other parameters. In a sense, the fuzzy if-then rules formalize what is known about plant responses to optical radiation (**Table** 1) and classify horticultural luminaire SPDs accordingly.

Summary

While light-emitting diodes have provided botanists with the ability to generate precisely-controlled SPDs for their research, the use of colloquial color names in their published papers has made it difficult to interpret and summarize their research results for the horticultural industry. This paper therefore proposes the use of a small number of radial basis functions to represent SPDs for horticultural lighting purposes, based on the observation that the absorption characteristics of photopigments in vivo limits the need for more detailed SPDs. A proposal for a horticultural spectral sensor that measures radial basis function weights directly is also introduced.

Finally, a fuzzy logic classifier is proposed as a means of representing expert knowledge gained from horticultural research using fuzzy if-then rules, thereby resolving the problem of determining the similarity of two or more SPDs for horticultural lighting purposes. ■

Wavelength	Weight	Very Low	Low	Medium	High	Very High
400 nm	0.03	0.88	0.12	0.00	0.00	0.00
425 nm	0.30	0.00	0.80	0.20	0.00	0.00
450 nm	0.66	0.00	0.00	0.36	0.64	0.00
475 nm	0.38	0.00	0.48	0.52	0.00	0.00
500 nm	0.39	0.00	0.44	0.56	0.00	0.00
525 nm	0.70	0.00	0.00	0.20	0.80	0.00
550 nm	0.88	0.00	0.00	0.00	0.48	0.52
575 nm	0.98	0.00	0.00	0.00	0.08	0.92
600 nm	1.00	0.00	0.00	0.00	0.00	1.00
625 nm	0.87	0.00	0.00	0.00	0.52	0.48
650 nm	0.63	0.00	0.48	0.52	0.00	0.00
675 nm	0.38	0.48	0.52	0.00	0.00	0.00
700 nm	0.15	0.40	0.60	0.00	0.00	0.00

Table 2: Fuzzification of 4000K white light LED SPD

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ABOUT THE AUTHOR

Ian ASHDOWN, P.Eng.(Ret), FIES: Ian Ashdown has over forty years of experience in research and development and development related to lighting design, including over 150 patents and patent applications. He is President and Senior Scientist for SunTracker Technologies, where he is developing lighting simulation software for horticultural, architectural and healthcare applications. He is currently focused on modeling germicidal ultraviolet-C radiation systems for the post-COVID world.

ABOUT SUNTRACKER

SunTracker provides professional lighting design software developed for the lighting industry beginning in 1996. In 1994, Senior Scientist Ian Ashdown authored Radiosity: A Programmer's Perspective (John Wiley & Sons). The software presented in this book has been under continual development since its publication, and is licensed to Lighting Analysts Inc. (Littleton, CO) for their AGi32, ElumTools, and Licaso products, and to Glamox AS (Molde, Norway) for their OptiWin 3D Pro architectural and marine lighting design software. In 2015, SunTracker recognized the need for horticultural lighting design software for greenhouses, polytunnels, and vertical farms. In addition to developing its Greenhouse Builder software, the company is working with academia on botanical research projects and with the American Society of Biological and Agricultural Engineers (ASABE), the Illuminating Engineering Society (IES), the Commission Internationale de l'Eclairage (CIE), and other organizations on the development of international standards for the lighting industry worldwide. Today, SunTracker is at the forefront of software development for horticultural, architectural, and entertainment lighting design.

UV LEDs in Disinfection and Sterilization

The global onset of the corona virus, COVID-19, has greatly increased interest in UV light applications for disinfection and sterilization. It has been known for many years the UV light can kill many forms of pathogens (germs), including bacteria, viruses, fungi and parasites. However, one must examine the effect on each type of germ carefully. This report will be confined to two applications that are of special interest at this time: drug-resistant bacteria and corona viruses. Concern about COVID-19 has led to an explosion of activity in research, the manufacturing of UV LEDs and the introduction of new products. In this summary we will try to include developments up until the end of April, 2020.

Introduction

Although visible light is confined to wavelengths between about 400 nm and 700 nm, ultra-violet (UV) light has many valuable uses, as illustrated in **Figure** 1, which is taken from the recent review by Hideki Hirayama [1].

Pathogen Deactivation

The ability of UV radiation to kill pathogens has led to great interest in their use in health care facilities, as illustrated in **Figure** 2 [2].

The wavelengths that are of special interest are UVC (200–290 nm) and near-UV (≈405 nm) light.

UVC light breaks the DNA of harmful micro-organisms to destroy them and must be used with great care, since it can also cause serious damage to humans and animals. Near-UV light is more selective, killing germs by causing photo-activation within their cells. The photons are absorbed by porphyrins, which exist inside the bacterial cell. The excited porphyrin molecules produce Reactive Oxygen Species (ROS) inside the cell. Intercellular oxidation damage occurs so that the cells lose bacterial membrane integrity and can no longer replicate.

For both wavelength ranges it is important to measure or calculate the dose that is being applied. This is done in terms of the amount of radiant energy per unit area, normally expressed in Joules per square centimetre (J//cm^2). If the power density is given (usually in W//cm^2), it is necessary to multiply this by the duration of the radiation in seconds.

A comprehensive list of the recommended dose requirements for many pathogens was published by the International Ultra-Violet Associations (IUVA) in 2018 [3].

The efficiency of pathogen reduction depends on the wavelength of the light, as shown in **Figure** 3.

This figure suggests that wavelengths below 240 nm might be particularly effective for viruses, but not for bacteria.

As noted above, two particular application areas have attracted special attention in recent years:

Healthcare Associated Infections (HAI):

Patients in hospitals often become infected with bacteria that are resistant to multiple drugs, such as Methicillin-resistant Staphylococcus aureus (MRSA) or Clostridium difficile (c.diff). It was reported at the 2020 NIST Workshop on UV Disinfection Technologies [5] that a 1000-fold reduction in activity has been achieved in laboratory experiments with doses of 10 J/cm^2 for MRSA and 46 J/cm^2 for C.diff. However, it has been shown that the rate of deactivation depends on the properties of the surface on which the virus lies.

Coronavirus:

Following the SARS-CoV outbreak in 2002, a joint team from the US National Institute of Health and the US Food and Drug Administration [6] showed that the virus is effectively deactivated by irradiation with UV-C light at 254 nm for 15 minutes at a dose of 4 mW/cm^2, corresponding to 3.6 J/cm^2. Very little effect was seen with UVA light at 365 nm.

A second form of corona virus emerged in 2012 and was called the Middle Eastern Respiratory Syndrome (MERS). Studies carried out at the University of Iowa in 2016 [7] showed that the activity of the MERS coronavirus was reduced by almost 6 orders of magnitude through 5 minutes of UV-C irradiation in a sample placed 4 feet from three xenon lamps from Surfacide. Neither the dose nor the spectrum was specified in the article.

Initial reports suggest that UVC radiation can also be effective against the COVID-19 coronavirus. Researchers from the Chinese Center for Disease Control and Prevention [8] found that COVID-19 coronavirus could be killed by irradiating with deep ultraviolet light with an intensity greater than 90 μW/cm^2 for 60 minutes (324 mJ/cm^2).

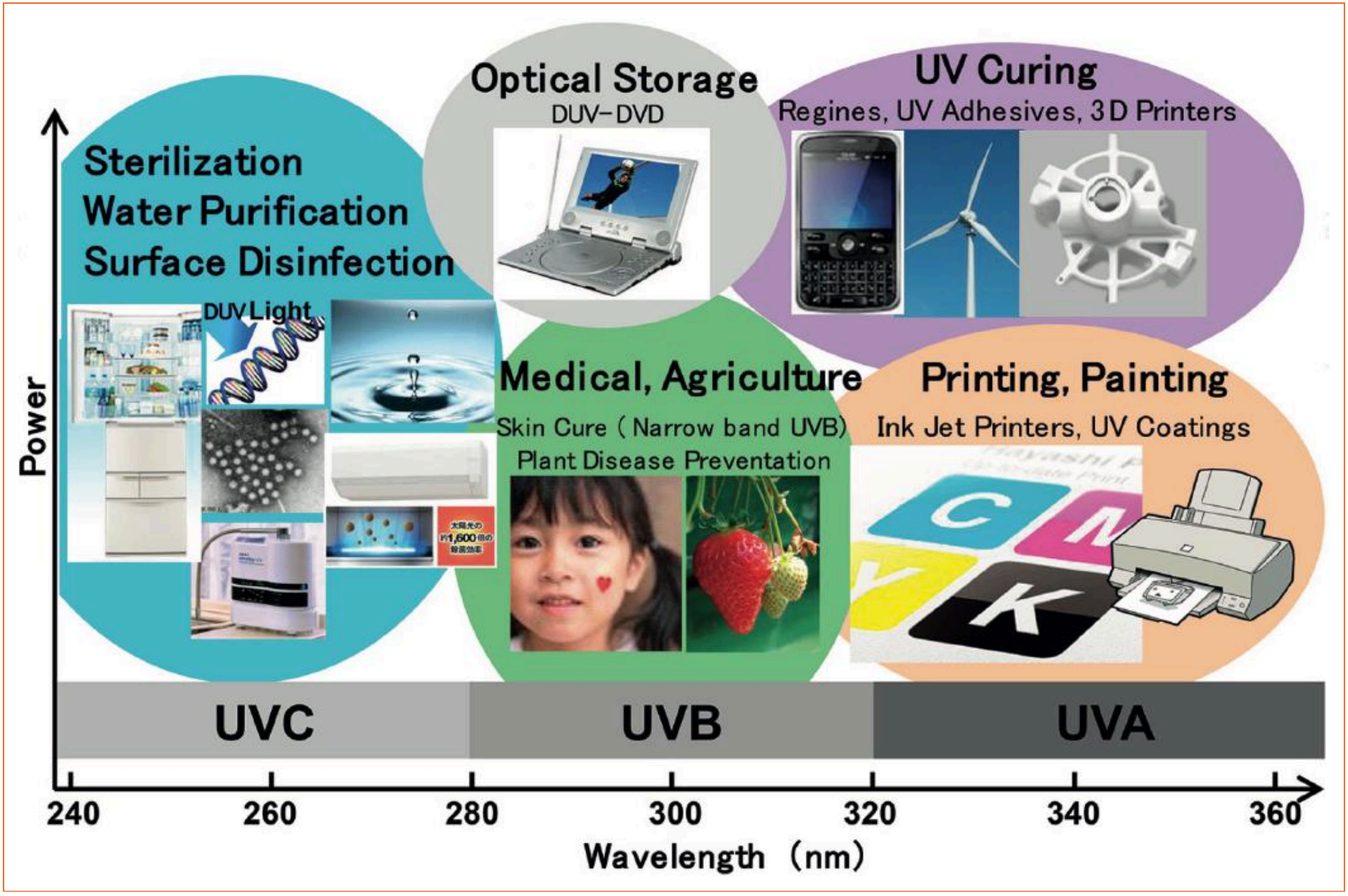

Figure 1: Uses of UV radiation (Hirayama, 2018)

Chen Jingwen of Hubei Shenzi Technology Co. [9] reported that a 10,000 fold reduction in activation can be achieved with a dose of 1085 mJ/cm^2. It must be stressed that in most applications, UV treatment is used in conjunction with other cleaning techniques and that normal rules of hygiene must be practised.

UVC Sources

The most common sources of UVC radiation are gas discharge lamps containing mercury (Hg). Hg atoms emit light strongly near 254 nm and 185 nm, although much of the shorter wavelength radiation is often absorbed in the glass tube containing the gas. Pulsed discharge lamps with xenon gas are also available and pulsed light might be more effective in some applications. These discharge lamps have been developed over many years and are highly efficient in producing UV light. However, these lamps warm up slowly and the lifetime of Hg lamps can be significantly reduced by frequent switching on and off.

There is growing interest in the use of UV LEDs for disinfection. However, up until now, UV LEDs have been very inefficient and expensive, as discussed below. In some applications the lower efficacy of current UVC-LED sources is offset by other advantages.

- The spectrum is tunable and can be limited to the most effective wavelengths for each application. Although light at 254 nm has been favoured in traditional lamps, this is not the optimal wavelength.
- Lifetime could in principal be much longer than that of traditional lamps. However, lifetime claims by some UV LED vendors may be overly optimistic.
- Warm-up time is very short and pulsed operation does not reduce the lifetime significantly
- The absence of mercury enables safer operation and simpler disposal procedures
- The low voltage DC operation allows the use of power from portable batteries
- The small size of LED sources provides more flexibility in the design of products and the control of the light distribution
- The smaller system footprint opens up applications that are not addressed well by traditional lamps. For example, UV-LEDs are currently recommended in water treatment for flow rates below 20 liters (5 gallons) per minute, while traditional lamps may still be preferred at higher flow rates [10].

A Chinese perspective on the relative merits of LED and traditional sources of UV in the present context has been given by Zhang Guohua, an engineering technology researcher of Qingdao Jiesheng Electric [11].

Efficacy and Cost of UV LEDs

The efficacy of current UV LED sources drops sharply below 360 nm, as shown, for example, by the database maintained by Kopp Glass [12]. The power conversion efficiency (PCE) of commercial UVC sources is around 3% or below, as shown in **Figure** 4. A compilation of data from company data sheets in April 2020 showed that the average PCE was 1.6% and only 11 out of 22 products claimed a value of 2% or higher. The efficiency of traditional UVC lamps is typically in the range 25%-40%.

The low efficiency limits the radiant output of UV-C LEDs. A 2018 report published

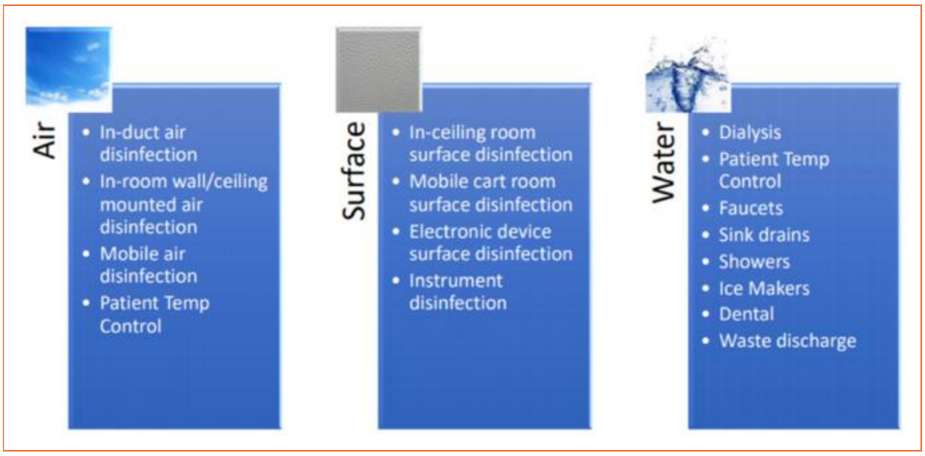

Figure 2: Health Care Applications of UV Light (IUVA)

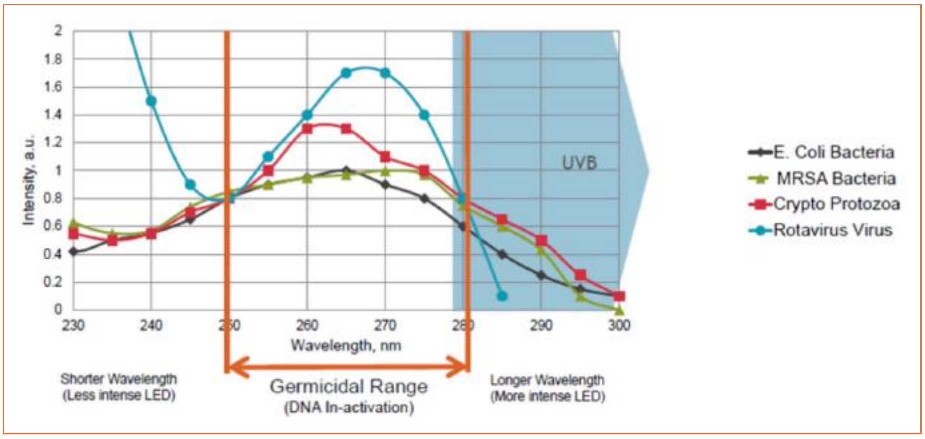

Figure 3: Wavelength dependence of absorption of deep UV light by pathogens (Crystal IS [4]

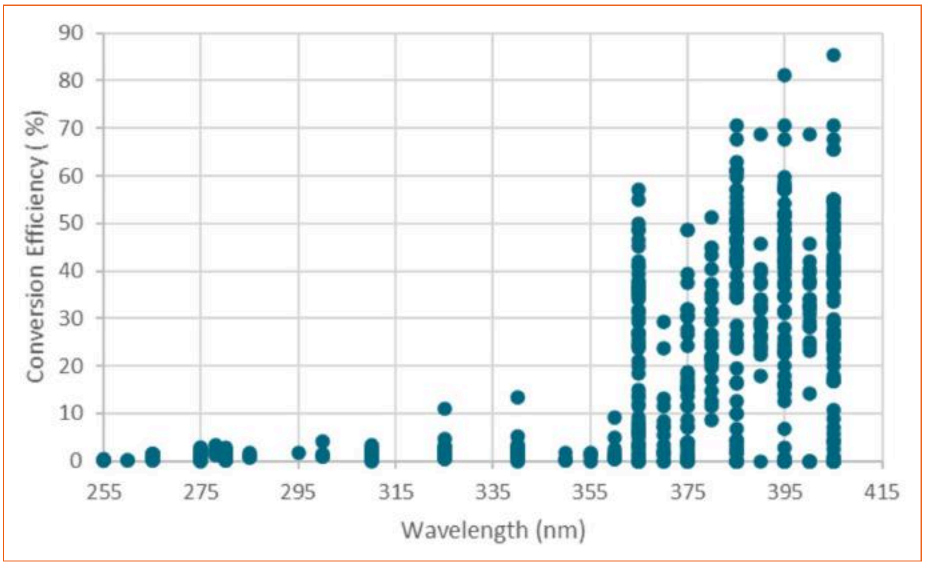

Figure 4: Claimed conversion efficiency of commercial UV LEDs

by the IUVA [13] showed that the available light from UV-C sources was less than 1% of that from LEDs at wavelengths over 365 nm.

There are many reasons why the efficacy of UVC LEDs is much less than that of light. These include:

- The band-gap of GaN is 3.4 eV, corresponding to a wavelength of 365 nm, which means that InGaN can be used to produce 405 nm light, but GaN has to be alloyed with AlN to produce UVC
- Poorer contacts and lower conductivity lead to less injection and conduction of charge
- Increased defect density leads to less photon production
- Light extraction is more difficult and requires more micropatterning
- Many of the components used in visible LED packages and lamps deteriorate quickly under UVC radiation

The feasibility of solving these problems has been demonstrated by many research laboratories in Asia [14], Europe [15] and North America [16]. For example, a collaboration between three laboratories in China [17] has used an innovative architecture to give a power conversion efficiency of 21.6%, but at low current density.

A comprehensive review of the development of UV LED technology has been provided by Yan Jianchang, a researcher of the Institute of Semiconductors of the Chinese Academy of Sciences and a deputy general manager of Shanxi Luoke UV Optoelectronics Technology [18].

On the assumption that focussed R&D can lead to the same rate of progress as in visible LEDs, Kneissl et al [19] forecast that the efficacy of commercial UVC LEDs could reach between 20% and 35% by 2025.

The low efficacy, along with the smaller market size, lead to much higher costs for UVC LEDs. **Figure** 5 shows that the purchase price of UVC-LEDs has come down substantially over the past twenty years.

By 2019 the price had come down further and was typically USD 0.50 to USD 1 per mW of radiant power on international markets. The entry of the major manufacturers in China and the potential increase in market size has already led to further reductions in the first few months of 2020 [20]. Nevertheless, the price is still two orders of magnitude above that of visible LEDs and that of traditional UVC lamps. It is clear that higher package efficacy is required, so that more light can be emitted from each LED, as well as improved manufacturing efficiencies.

Avoiding Damage from UV Light

The risks to humans and animals from UV radiation are well documented, for example in the CIE report 187:2010 “Photocarcinogenesis Risks from Germicidal Lamps” [21]. Great care has to be taken in using UV-C systems in environments in which humans are present.

Most researchers and vendors have concluded that near-UV light at ≈ 405 nm can be used where people are present. Research on mice carried out in the US [22], Japan [23] and Scotland [24] has suggested that UVC light near 222 nm may also cause less serious damage to skin than light at wavelengths in the range normally used (250–290 nm). This is primarily because the radiation is absorbed in the outer layers of the skin and does not penetrate to the deeper levels at which cancer develops. This finding deserves further research.

Extra care needs to be taken in choosing the materials that are used in LED packages and light delivery systems. This leads to difficult choices in balancing performance and lifetime against cost. These challenges have been discussed at length by Wu Qian, general manager of Guangzhou Hongli Bingyi Optoelectronics Technology [25].

Proponents of UV LEDs often argue the greater reliability will help offset the higher purchase cost and lead to lower total cost of operation. However, the lifetime of well-designed mercury lamps is over 10,000 hours, while the claims by some vendors for longer lifetimes in LED systems have yet to be verified. Although some suppliers of UV LEDs claim lifetimes up to 50,000 hours, more conservative companies promise only 1000 hours.

Light Delivery

Since UV photons are expensive and potentially dangerous, care must be taken in controlling the distribution of light leaving the source. This is particularly true for the two applications discussed here in which germs can be spread widely in the air and on surfaces.

A: Air Cleaning

Upper-room UVC units have been used in schools since the 1930s and can be installed in classrooms, cafés, gymnasiums and childcare centres, as well as in health care facilities—anywhere infectious agents may exist. The Illuminating Engineering Society (IES) recommends [26] that UVC sources be installed at a height of around 2.2 feet with the light emitted upwards, as shown in **Figure** 6.

Air conditioning systems should be used to recycle and mix the air, at a rate equivalent to at least 6 air changes per hour. Applying UV irradiation within the air conditioning system can also be effective, especially when the light is directed onto filters or heat-exchange surfaces [27], as shown in **Figure** 7.

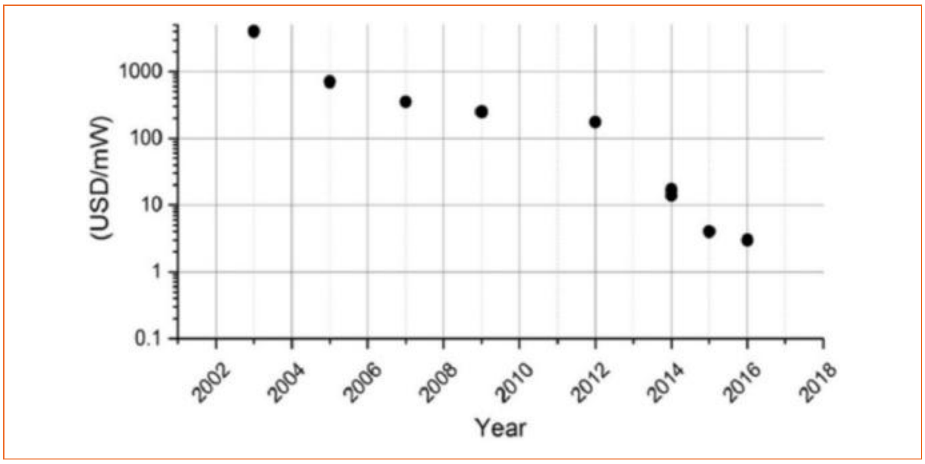

Figure 5: Prices of UVC LEDs 2003-2016 (AquiSense Technologies)

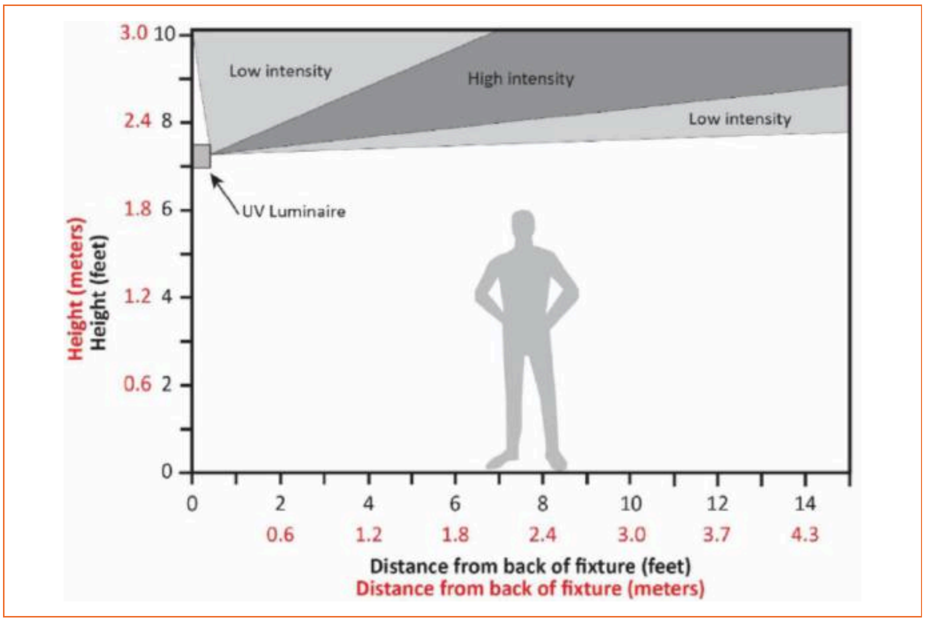

Figure 6: Distribution of light from UV sources in upper room disinfection (IES)

B: Surface Cleaning

Surfaces in rooms or areas that are not in use can be disinfected in-situ by UVC irradiation, usually in conjunction with other cleaning methods. Care must be taken in source placement to avoid shadowing and ensure that each surface receives the required dose. Portable items, such as stethoscopes or kitchen tools, or personal protection equipment, such as gloves and masks, can be removed and treated in specially designed chambers.

For rooms that are not occupied for several hours each day or week, strong UV radiation can be applied. For example, several companies [28] have adapted troffers or downlights by adding 405 nm LEDs in order to combat bacteria. When people are present, a modest amount of near-UV light is mixed with white light. When the rooms are not being used, the lamps emit just UV light.

A more futuristic approach to room cleaning is to use robots that can see what is being irradiated as they move around and switch themselves off if they detect the presence of humans or animals [29].

In some situations, such as for moving handrails on powered walkways and escalators, devices can be designed for continuous operation even in the presence of people by ensuring that no UV light escapes [30].

There are some applications where traditional surface cleaning techniques, such as chlorine wipes, cannot be used. For example, a team in Korea has shown that by irradiating sliced cheese for 10 min at a dosage of 3 mJ/cm^2, ca. 99.99% of the pathogens were inactivated without affecting quality changes in color or generating significant numbers of injured cells [31].

C: Embedded UV Emitters

As shown in **Figure** 8, UV emitters can be incorporated in many appliances and consumer products. The small size of LED systems and low voltage drive will accelerate such adoption. However, manufacturers of products incorporating UV sources must take care to ensure that the components that are irradiated by the UV light do not deteriorate within the lifetime of the product.

Summary

UV light has the potential to save many lives, especially through attacking the germs that lead to infection in health care facilities and slowing the spread of viruses. However, despite rapid progress over the past twenty years, the low efficiency and high cost of UV LEDs hinders their wide adoption, especially in countries with under-developed economies. Further R&D and innovative manufacturing techniques will be needed so that the full potential of this technology can be realized.

The impact of UV light on humans and other animals is not yet fully understood. Great care must be taken in applying this technology.

The situation is evolving rapidly and much information is being made available over the internet. For example, under the guidance of the National Semiconductor Lighting Engineering R&D and Industry Alliance and the Third Generation Semiconductor Industry Technology Innovation Strategic Alliance, the China Semiconductor Lighting Network [32] has published a series of tutorials on the internet which can be translated by Google. These cover a wide range of topics from a detailed discussion of the effects of UV on pathogens and the potential dangers to human health [33][34], to the history and growth prospects of the UV LED industry [35].

However, all information that is communicated over the internet must be validated by sources that you trust, especially when it concerns human health. Readers are recommended to follow the advice that is being provided by respected sources, such as the International Ultraviolet Association [36] and the Illumination Engineering Society [37]. ■

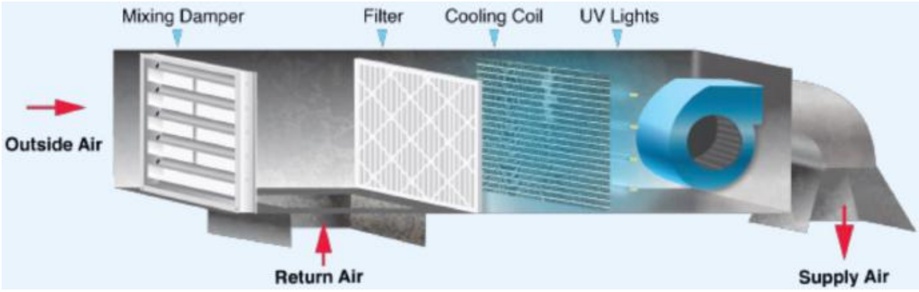

Figure 7: UV disinfection in air conditioning systems (Ultra Violet Devices Inc)

CATEGORY	APPLICATION AREA	REQUIREMENT	LED SOLUTION
Living	Washing machines	Water for rinsing, detergent slot	UV-C
		Deodorizing clothes	UV-A + TiO2
	Dryers	Heat exchanger surface	UV-C
	Cloth managing machines		
	Vacuum cleaners	Charging station	UV-C
		Dust canisters	405nm
Kitchen	Refrigerators	Water dispenser faucet tip	UV-C
		Deodorization	UV-A + TiO2
	Ovens	Tray, kitchen tools	UV-C
	Water purifiers	Water dispenser faucet tip, water tank	UV-C
	Dish washers	Filter, remaining water	UV-C
Air	Air conditioners	Drain fan	UV-C
		Heat exchanger surface	405nm
	Air purifiers	Deodorization, inner space disinfection	405nm
Consumer electronics	Skincare product sterilizers	Sterilization of 'skin contact area'	UV-C
	Escalator handrail sterilizers	Sterilization of handle	UV-C
Bio-medical	Psoriasis treatment	Eliminating activated immune cells (T-cells)	UV-B

Figure 8: Potential use of UV LEDs in appliances and consumer devices (LG Innotek)

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Open-Source LIDAR Prototyping Platform

This article discusses Analog Devices' new broad market LIDAR prototyping platform and how it helps shorten the customers' product development time by providing a complete hardware and software solution that customers can use to prototype their algorithms and custom hardware solutions. It goes over the details of the modular hardware design, including the light receive and transmit signal chains, FPGA interface, and optics for long range sensing. The system partitioning decisions that were made are explained, helping highlight the importance of good system design, interface definition, and right level of modularity. The components of the open source LIDAR software stack and the platform specific API are described showing how customers can benefit from these during product development and integrate them in their final solutions.

As autonomous vehicles and robots continue to move from science fiction to reality, automotive and industrial customers are seeking new environment perception solutions to enable these machines to navigate autonomously. LIDAR is one of the fastest growing technologies in this field and is seeing wider adoption as the technology becomes more mature and reliable, opening up a huge market opportunity. As many startups and well renowned sensor companies are working toward developing more precise, less power hungry, smaller form factor, and more cost-effective LIDAR sensors, they all face the same challenges when it comes to system hardware design and implementing the software infrastructure to talk to all the components in the system. These are the exact areas where ADI can bring value through hardware reference designs accompanied by open-source software stacks, enabling customers to easily integrate into their products ICs from the ADI LIDAR portfolio, as well as software modules and HDL IPs, shortening their time to market.

System Architecture

As customers develop their LIDAR sensors, there are few areas of differentiation in the system design: receive and transmit optics, number and orientation of lasers, laser firing patterns, laser beam steering, and number of light receive elements. But, regardless of these choices, there is a high degree of commonality in the receive signal chain and laser drive signal requirements. Based on these assumptions, Analog Devices designed a modular LIDAR prototyping platform, AD-FMCLIDAR1-EBZ, intended to allow customers to easily configure or replace parts of the design with their own hardware, designed according to specific applications requirements, but still be able to use the platform as a whole system. The system is partitioned into three different boards with standardized digital and analog interfaces:

- A data acquisition (DAQ) board containing a high speed JESD204B ADC and corresponding clocking and power. This board has an FMC compliant interface to connect to the users' preferred FPGA development board. It serves as the baseboard in the system by having the other two boards connected to it via digital connectors that route control and feedback signals between these boards and the FPGA and through coaxial cables for analog signals.
- An analog front-end (AFE) board containing the avalanche photodetector (APD) light sensor and the entire signal chain required for conditioning the APD output signal so that it can be fed into the ADC on the DAQ board.
- A laser board containing the lasers and drive circuit.

As always, in system design, modularity means flexibility, but it also comes with drawbacks such as increased complexity, performance degradation, and increased cost, which must be thoroughly evaluated when deciding on the system partitioning. In this case, the system was broken down into these three boards for the following reasons:

- The ADC and clocking are very likely to stay the same regardless of the implementation of the analog front end and chosen laser solution.
- The analog front-end hardware design and form factor is subject to change depending on the chosen APD, overall system receive sensitivity, and chosen optics.
- The laser board design and form factor are also subject to change depending on the chosen illumination solution and optics.
- The system must provide a lot of flexibility in positioning and orienting the receiver and the transmitter so that they are aligned with each other or other targets, which is why flex cables are being used for the digital signals and coaxial cables for the analog signals that go between the boards.

The software stack that accompanies the hardware design is based on a hierarchical approach with a few layers dividing it into OS specific drivers and interfaces, a system specific API, and an application layer.

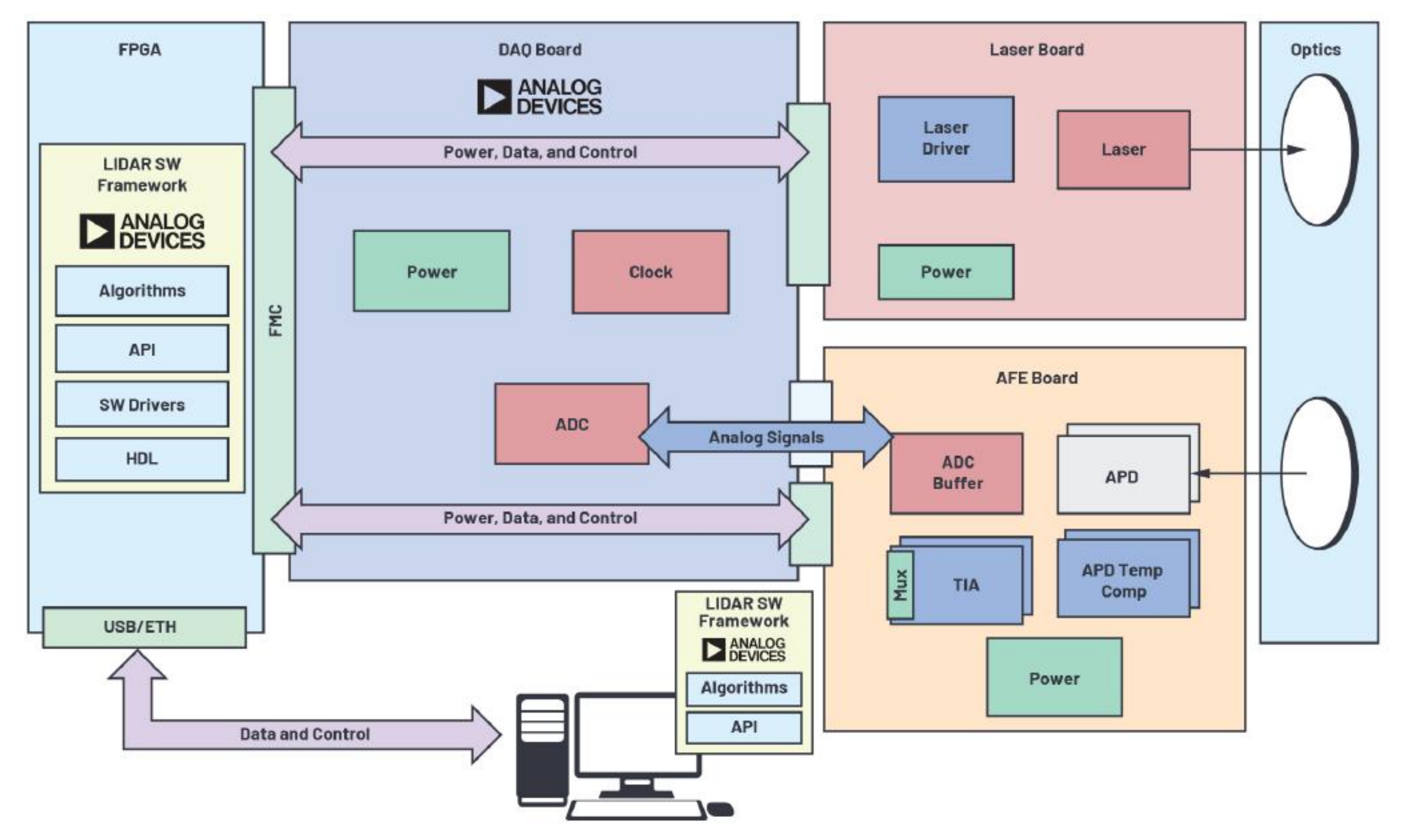

Figure 1: LIDAR platform system design

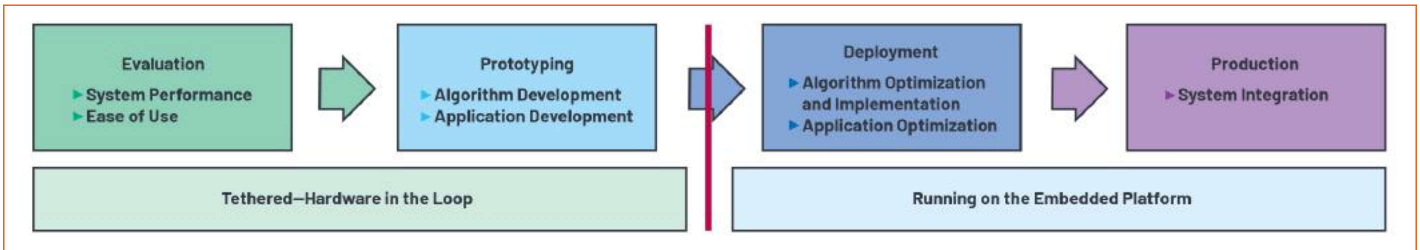

Figure 2: Product development cycle

This allows the upper layers of the stack to remain unchanged regardless of whether the software is running on an embedded target or a PC talking to the system via the network or a USB connection. This is very valuable in the different product development stages, shown in **Figure** 2, since it means that the same application software that was developed during the prototyping stages, when the system is tethered to a PC for ease of development, can be easily deployed onto the embedded production system without ever touching the low level interfaces.

Hardware Design

A LIDAR sensor computes the distance to a target by measuring the time it takes for the light pulse to travel to the target and back. The time is measured in increments of the ADC sampling rate since that determines the resolution with which the system samples the received light pulse.

Equation (1) shows how the distance is computed relative to the ADC sampling rate.

$$d = N \cdot \frac{L_s}{2 \cdot f_s} \qquad (1)$$

Where:

- L_s is the speed of light, 3×10^8 m/s
- f_s is the ADC sampling rate
- N is the number of ADC samples since the light pulse is generated until it is received back

Given the 1 GHz sampling rate of the AD9094 JESD204B quad ADC being used in the system, the results of each sample correspond to a distance of 15 cm. For this reason, it is critical that there aren't any sampling uncertainties in the system since even an uncertainty of a few samples can result in large distance measurement errors. Traditionally, LIDAR systems are based on parallel ADCs that inherently provide zero sampling uncertainty. As the number of receive channels keeps increasing and the power and PCB size requirements become more stringent, these types of ADCs do not scale well. Another option is to use ADCs with high speed serial outputs, such as JESD204B, which solve the issues the parallel ADCs have. This option comes with an increased complexity on the data interface and makes it harder to achieve zero sampling uncertainty.

The LIDAR DAQ board provides a solution to these challenges by showing how to design the power, clocking, and data interface for a JESD204B data acquisition system operating in Subclass 1 mode, ensuring deterministic latency so that zero sampling uncertainty can be achieved, while taking advantage of all the benefits that the JESD204B interface provides and having the lowest possible power for the clocking scheme. To operate in JESD204B

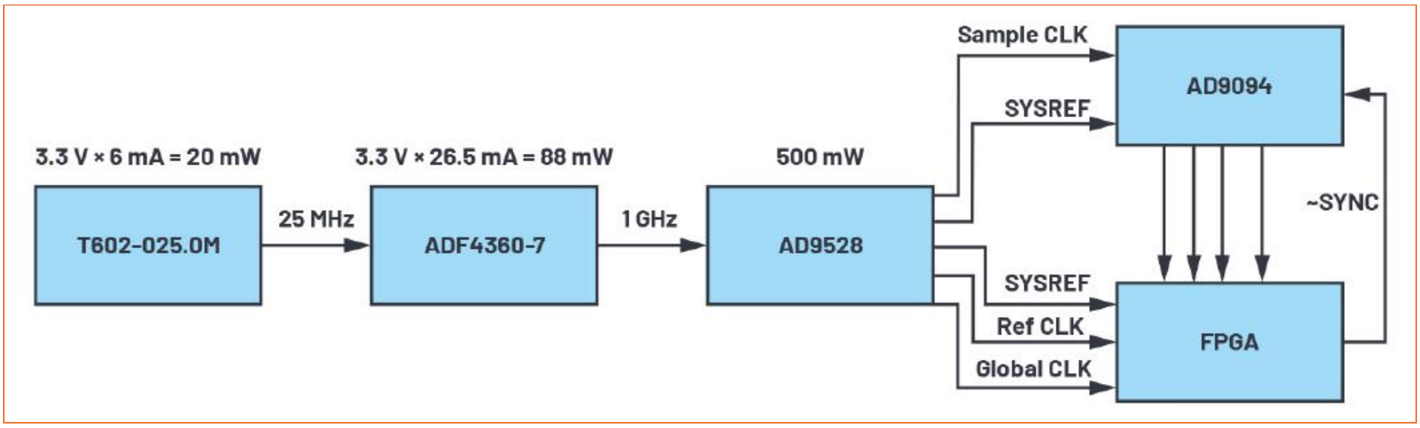

Figure 3: DAQ board clocking and data path

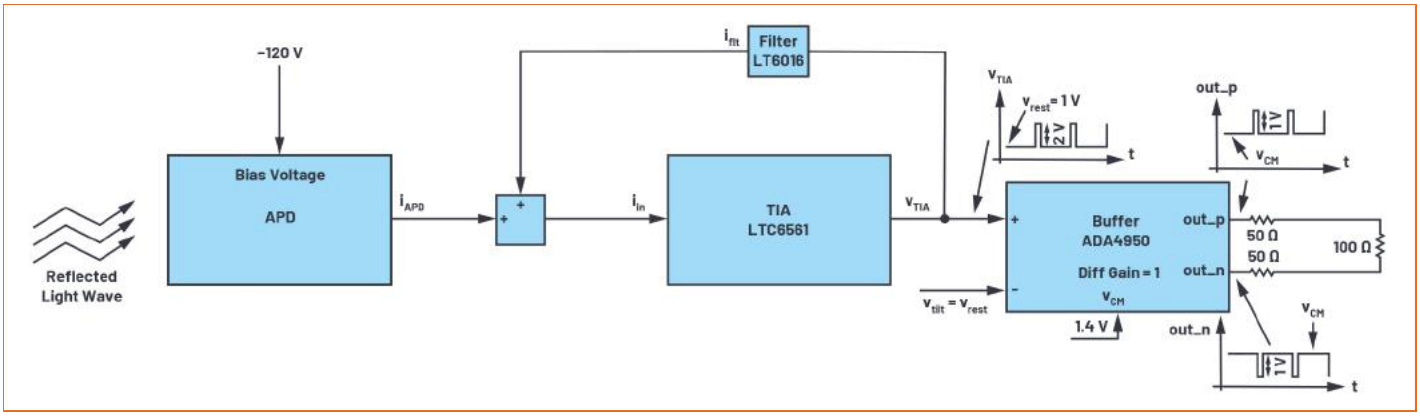

Figure 4: AFE board signal chain

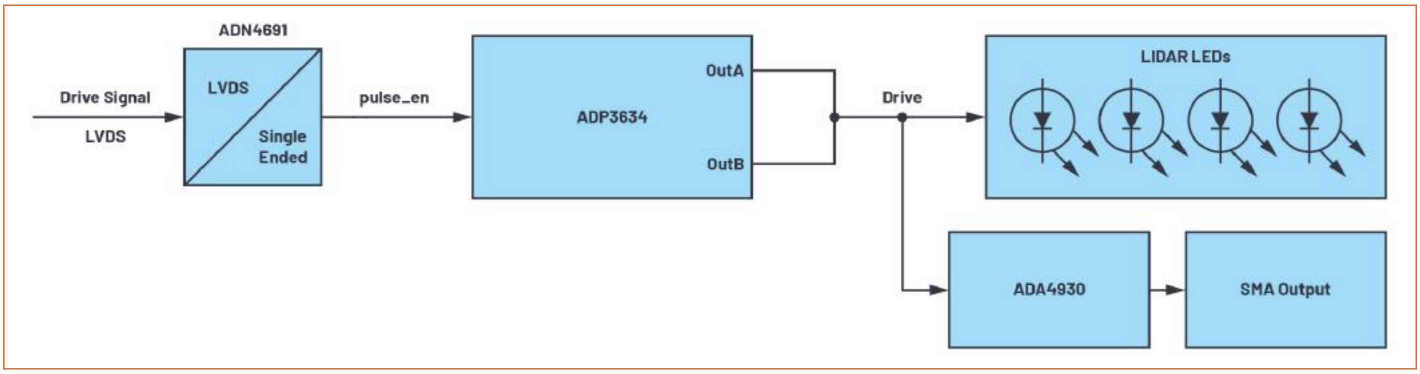

Figure 5: Laser board signal chain

Subclass 1 mode, there is a total of five clocks needed in the system:

- ADC sampling clock: drives the ADC signal sampling process.
- ADC and FPGA SYSREF: source synchronous, high slew rate timing resolution signals responsible for resetting device clock dividers to ensure deterministic latency.
- FPGA global clock (also referenced as core clock or device clock): drives the output of the JESD204B PHY layer and FPGA logic.
- FPGA reference clock: generates the PHY layer internal clocks needed by the JESD204B transceivers; needs to be equal to or an integer multiple of the device clock.

All the clocks are generated by one AD9528 JESD204B clock generator, thus ensuring they are all synchronized with each other. **Figure** 3 shows the clocking scheme and the data interface with the FPGA.

The AFE board receives the optical reflected signal, converts it to an electrical signal, and transfers it to the ADC on the DAQ board. This board is probably the most sensitive part of the entire design since it mixes signal condition circuits working with microampere current signals generated by the 16-channel APD array, converting the optical signal to an electrical signal, with high voltage power supplies in the range of –120 V to –300 V needed to power the same APD. The 16 current outputs are fed into four low noise, four-channel, transimpedance amplifier (TIA) LTC6561s with an internal 4-to-1 mux to select the output channel that is afterward fed into one of the four ADC inputs. The input section of the TIAs needs a lot of attention to achieve the desired level of signal integrity and channel isolation so that there is no additional noise added to the very low current signal generated by the APD, thus maximizing the SNR and the object detection rate of the system. The design of the AFE board shows the best practices to achieve the maximum signal quality by keeping the length of the traces between the APD and the TIA as short as possible, adding vias in between the TIA inputs for maximum channel-to-channel isolation, and positioning the signal condition circuits so that they do not interfere with the other power circuits on the board. Another important feature is the ability to measure the temperature of the APD to be able to compensate for APD signal output variations due to temperature changes as the APD's temperature increases during normal operation. A few knobs are provided to control the offsets of the signal chain and the APD bias, which translates into APD sensitivity, to be able to maximize the ADC input range for maximum SNR. **Figure** 4 shows a block diagram of the AFE board signal chain.

The laser board generates the optical pulses with a wavelength of 905 nm. It uses four lasers that are driven simultaneously for an increase in beam strength, resulting in a longer measurement range. A PWM signal generated by the FPGA carrier board with programmable pulse width and frequency is used to control the lasers. The signal is generated on the FPGA as LVDS to make it less susceptible to noise as it travels from the FPGA to the laser board through the DAQ board and the ribbon cable connecting the DAQ and the laser boards. The drive signal can be fed back to one of the ADC channels for time of flight reference. An external power supply is used to power the lasers. The design complies with International Standards IEC 60825-1:2014 and IEC 60825-1:2007 for a Class 1 laser product.

Both the AFE and laser boards require optics for long distance operation. The system was proven to operate at 60 m using fast axis collimators [1] for the laser diodes that narrow the vertical FoV to 1° while keeping the horizontal field of view unchanged, and an aspherical lens for the receive side.

HDL Reference Design

The HDL design constitutes the primary interface to the hardware and implements all the logic to transfer data from the JESD link to the system's memory, drive the lasers, synchronize the receiver and transmitter for accurate time of flight measurement, and implement the communication interfaces to all the components in the hardware design. **Figure** 6 shows a simplified block diagram of the HDL design. The generic architecture of the ADI's HDL reference designs makes the framework scalable and

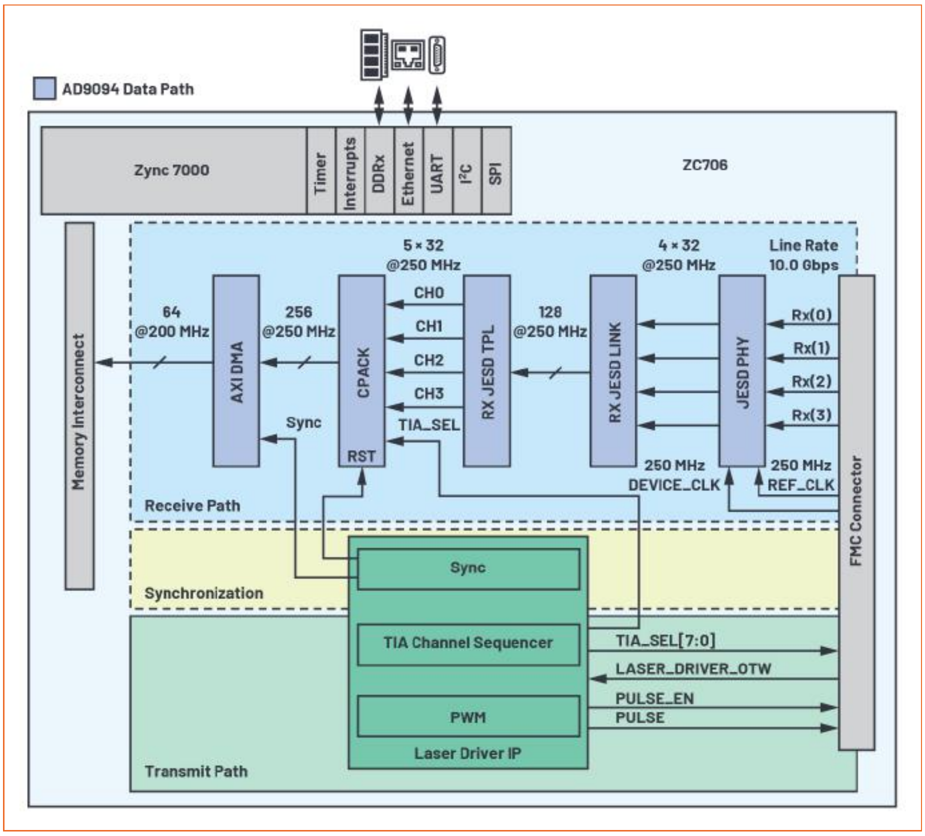

Figure 6: HDL design block diagram

more accessible to port to another FPGA carrier. The design is using the Analog Devices JESD204B framework [2] along with several SPI and GPIO interfaces to receive data from the AD9094 ADC and to control all the devices on the prototyping platform.

The JESD204 link is configured to support four data converters (M) using four lanes (L) with a lane rate of 10 Gbps for a converter resolution of eight bits. The device clock, which will be the same as the reference clock for the high speed transceivers, is set to 250 MHz and is provided by the DAQ board. The link is running in Subclass 1 mode, which ensures deterministic latency between the high speed converter and FPGA.

One of the biggest challenges of a LIDAR system is how to synchronize various functions to the transmitted pulse and how to process just the necessary amount of data, received from the high speed ADC. To address this, the HDL design contains an IP that provides the required logic to generate a laser pulse, control the internal multiplexers of the TIAs and provides a backpressure for the DMA. All these control functions are synchronized with the transmitted pulse, so the system doesn't have to save all the raw digitized high speed data stream. This way, the overall data rate of the system is highly reduced.

Software

The key points that define the software stack for the LIDAR platform are free and open source. The user gets through them the "freedom to run, copy, distribute, study, change, and improve the software[3]. Starting from the Linux® kernel and continuing with the user space tools, everything respects this.

The software drivers implemented in the kernel initialize the hardware components and expose to the user all their useful functionalities. Most of these drivers are part of the Industrial I/O (IIO) Linux subsystem [4]. The drivers are all platform agnostic, so hardware changes, including carrier ones (for example, migrating from a Xilinx® FPGA to an Intel® one), do not require them to be changed.

To ease the development of software interfacing IIO devices, ADI has developed the libiio library [5]. It abstracts the low level details of the hardware and provides a simple yet complete programming interface that can be used for advanced projects. The various available libiio back ends (for example, local, network, USB, serial) make possible the usage of IIO devices locally and remotely from applications running on different operating systems (for example, Linux, Windows®, macOS®).

The IIO oscilloscope, developed by ADI, is an example of an application that uses libiio to interface with IIO devices and can be used during the system evaluation stage. The tool can capture and plot data in different modes (for example, time domain, frequency domain, constellation, cross-correlation), transmit data, and allow users to view and modify the settings of the detected devices.

While libiio provides a low level programming interface, in most cases, users expect a platform-specific API that abstracts the low level driver calls and exposes a set of functions to access and configure the various system parameters and stream data from the system. For this reason, the LIDAR prototyping platform comes with a specific API with bindings for popular frameworks and programming languages such as C/C++, MATLAB®, or Python® [6], enabling users to interface with the system using their preferred programming language and focus on algorithms and applications, which is the value proposed to their customers.

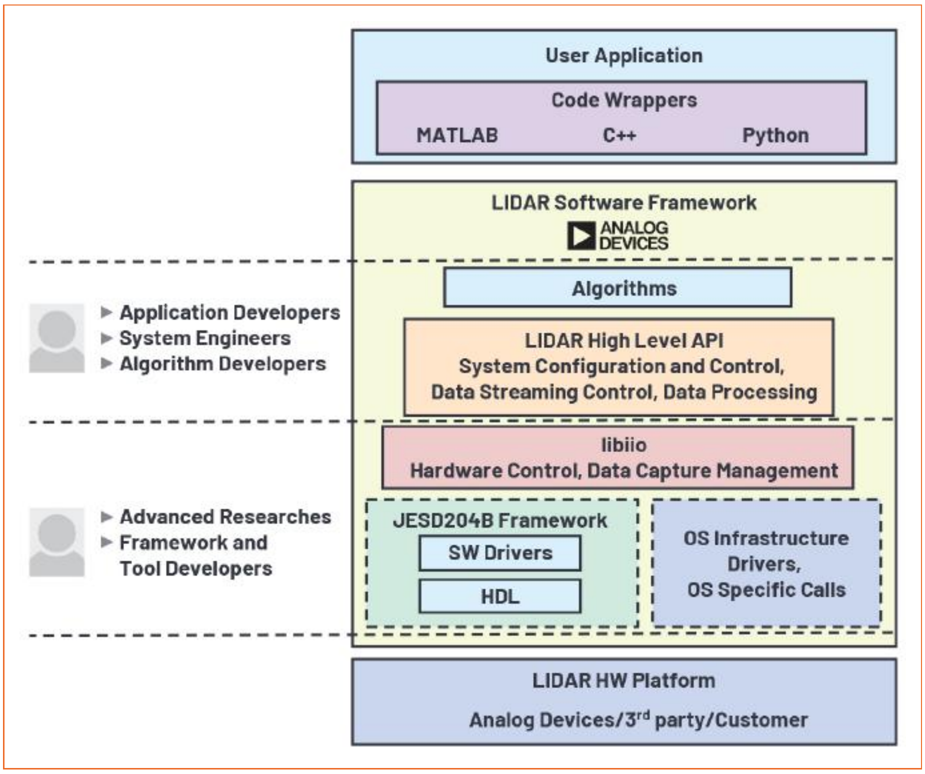

Figure 7: Software stack

Conclusion

In any system design, when the architecture is being established and design decisions are being made, there is a certain degree of ambiguity. This represents the risk that the system will not work or perform as expected after being built, resulting in multiple design cycles, increased development cost, and longer time to market for a product. Being built on pre-engineered systems intended to interoperate with each other, reference designs reduce risk and improve overall predictability and reliability as compared to using a custom, one-off design built from scratch. Using a reference design as a starting point in the planning process helps bring new designs to market faster and helps ensure there are fewer surprises and problems. System designers are always seeking reference platforms to prove out the design decisions, thus reducing the risk and improving reliability. Starting a project with clear and standardized design options facilitates the planning process. It does so by using a common language to help align goals, encourage cooperation and participation across multiple functions, and make it easier to evaluate the tradeoffs between design goals. The LIDAR prototyping platform tries to meet these needs by providing open-source hardware and software designs that can be referenced in the initial system architecture phases. The hardware platform and the software stack can be used through all the phases of product development, from initial system evaluation, development, and integration into the final product. The contents of the reference design such as engineering drawings and a BOM provide a head start in getting to buildable, legal, and localized design system. This shortens the design cycle and likely saves money in the process. The modular hardware design allows various configuration options to meet the specific application requirements, while the open-source software stack, based on industry-standard frameworks and programming languages, and accompanied by application examples, allows customers to focus on developing the applications that bring value to their products without having to spend effort on the low level portions of the stack. ■

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BlackBody I.RAIN OLED luminaire showcased at Lighting Japan

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Interview: LiFi

For over a decade, research in LiFi has been intensified with amazing results. Musa Unmehopa Head of Ecosystems and Strategic Alliances for LiFi at Signify, an avant-gardist company in this domain, told LED professional about the status of LiFi and his plans for the future. ■

Infrared Thermography

An alternative contact-free method, high-speed thermography, is proposed in this work. The potential of transient temperature measurements and its process are described, the results of the analysis are demonstrated and the benefits are explained. ■

Thermo-Transfer Technology

The author describes a novel thermo-transfer technology combined with high impact light source that promises to change the poor quality, efficacy, luminous flux and overall light quality of the MR16 form factor. ■

Digital AC Direct LED Driver Control

The authors propose such an IP protected solution for LED lighting applications that offers high efficiency and an extremely reduced form factor, to name just a few features. They also explain the working principle and its applications. ■

Inductor Technologies for Automotive Lighting

The authors propose an IP protected solution for LED lighting applications that offers high efficiency and an extremely reduced form factor. They also explain the working principle and its applications. ■

New Metric for Artificial Light Sources

This article presents a new metric, Average Spectral Difference (ASD), which provides a quantitative measurement of how closely a light source matches the spectra of natural light. ■

Full Spectrum LED Study

To consolidate existing knowledge and gain new knowledge on recently introduced Full Spectrum LEDs, which claim to bring natural light quality into electric lighting appliances, a psychological study was conducted. The latest results from this study are presented and discussed. ■

Updates

LpS Digital, Regulation News, Industry News, Commentary and Editorial. ■

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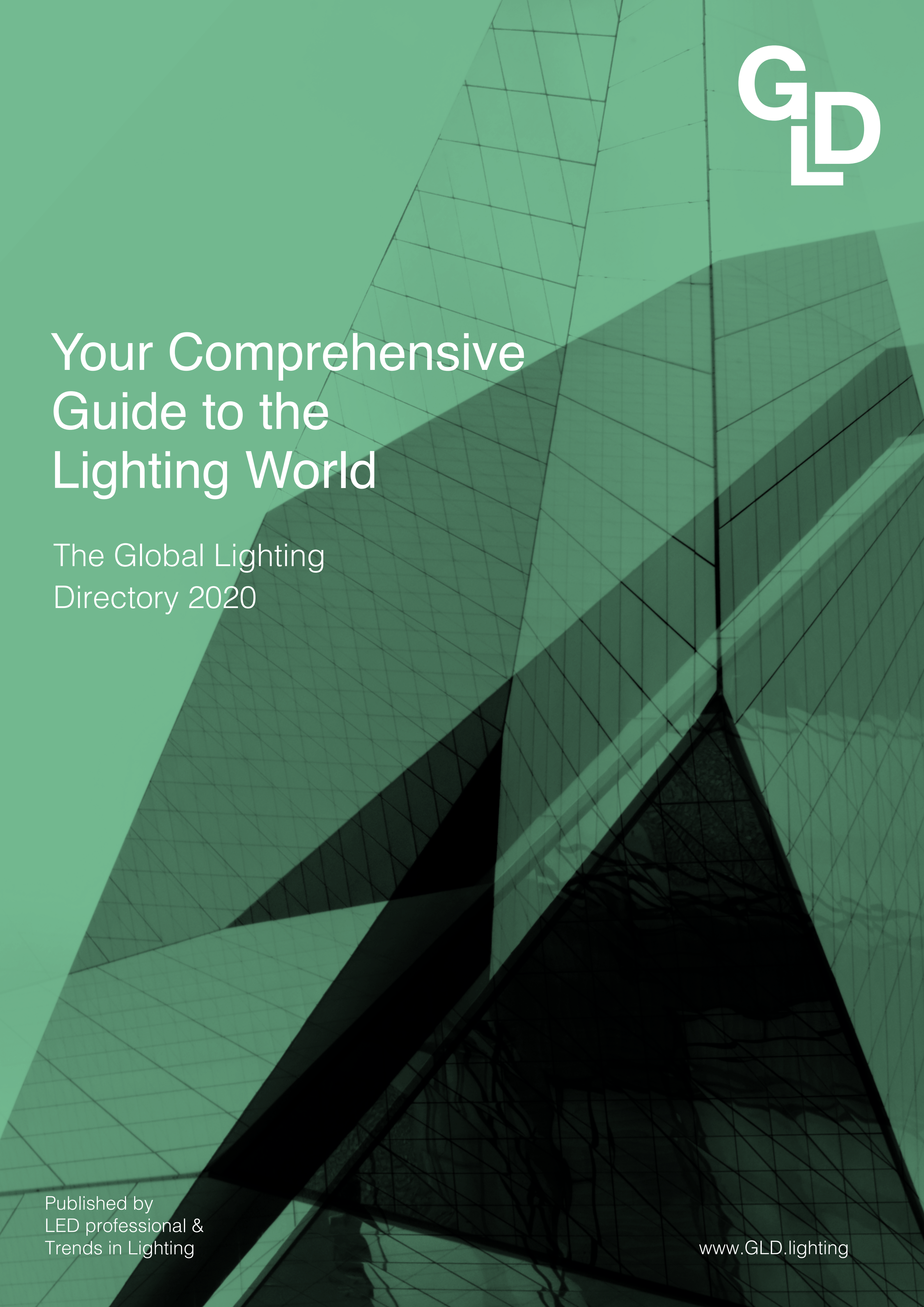

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