

LIGHTING TECHNOLOGY

Information DISPLAY

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A Promising New Age of Lighting

BIOLOGICAL EFFECTS OF LIGHTING

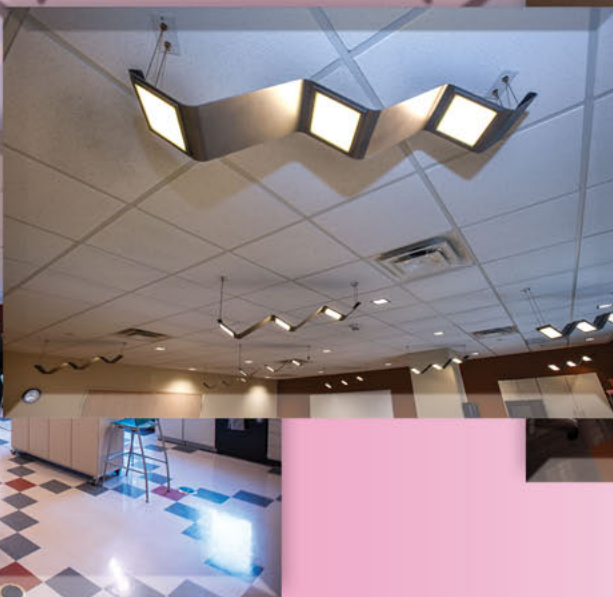
**OLED CREATES A BRIGHTER
MARKET FOR LIGHTING**

HIGH-RES LCD HEADLAMPS

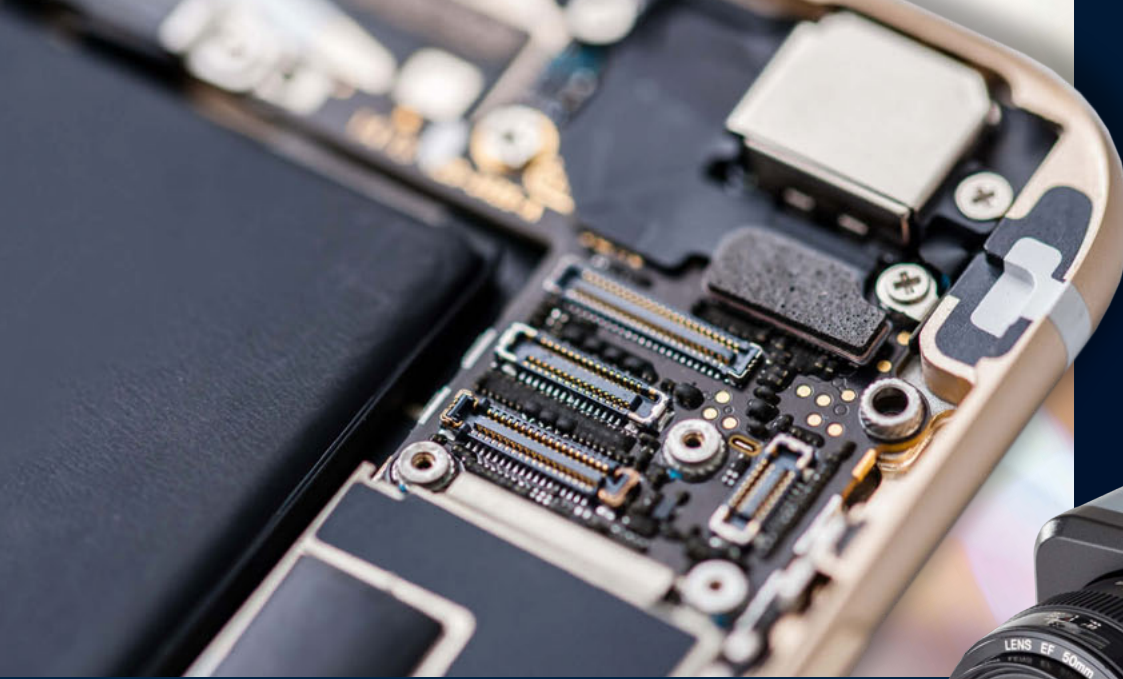
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ON THE COVER: The four lighting installation images featured on our cover were created with OLED panels from OLEDWorks in Rochester, New York. The top left image features the Petal luminaire from Visa Lighting; the bottom two left-hand images are Limit luminaires, also from Visa Lighting; and the bottom right image is the Trilia luminaire from Acuity Brands Lighting.



Cover Design: Jodi Buckley

In the Next Issue of Information Display

Emissive Technology and Pre-Display Week Coverage

- Disruptive Emissive Technology
- SID Honors and Awards Winners
- DW 2018 Symposium Preview
- Best Displays at CES 2018

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Lighting the Way into a New Year

by Stephen P. Atwood

Welcome to 2018. Once again we embark on a new year with great hopes and many new technical innovations on the horizon. It's an extremely fertile time in our industry, with many rapid advancements in fields such as augmented reality, artificial intelligence, wearable technologies, quantum dots, and of course OLEDs. In this issue we turn our

attention to lighting, including new advances in OLED lighting, new understanding of how the spectrum of light affects our health, and new ways in which traditional display technology can be leveraged to shift the paradigm of automotive lighting technology. This and much more await you in this first issue of *Information Display* for 2018.

Environmental ambient lighting technology is a topic of interest for me for personal reasons. I have always found harsh and direct task lighting uncomfortable for work. Lamps with bright beams that point directly at my work surface produce glare that affects my eyes' ability to focus and causes headaches. To avoid this I tend to use a lot of bright light around the room, which is inefficient. As I have aged, I notice that I need even more light to focus on small things, and I sometimes resort to using flashlights at specific angles that I can control. But the angle needs to be just right, and if I can see any part of the beam directly, this method doesn't help me. For the above reasons, I now prefer the even lighting of digital screens to paper and tend to use my tablet much more than books.

Apparently I'm compensating for existing lighting equipment that is neither ergonomically designed nor well suited for my use. And I suspect my experience isn't unique. I find this discomfort with lighting also affects my mood. Spending time in small spaces, such as airplanes, with poorly designed or dingy lighting only makes the experience less appealing. Dining in a dimly lit restaurant can be romantic for some people, but does not enhance the experience for me. Neither does an extremely bright or harsh industrial environment with overly bluish-white lighting.

Therefore, I can really appreciate the work of people who study the effects of lighting on people's well-being. An open space with well-designed ergonomic lighting, whether it be for work or play, makes a big difference in the quality of the experience. I've thought for years about how I could remodel the rooms in my home and office with wide-sweeping indirect lighting with adjustable color temperature and intensity. I've marveled at some of the more recent commercial spaces I've seen where the ambient light is bright and neutral in tone, and seems to come from everywhere but nowhere in particular.

Although the basic design of indoor lighting fixtures has changed very little over the past few decades, significant advancements of the kind mentioned above are starting to be made. I believe even more progress will be enabled by the latest developments in OLED technology.

So I am excited about our issue lineup featuring a pair of articles developed by our guest editor, Marina Kondakova. Marina is the director of device formulation at OLEDWorks and a chair of the Display Week 2018 technical program sub-committee for lighting. She is also someone who has thoughtfully considered how better lighting technology can improve our lives in many ways. I encourage you to read her guest editorial, which sets the stage for these important pieces.

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industry news

By Jenny Donelan

LG Display Intensifies OLED Lighting Push

LG Display continues to promote OLED TV technology (see Product Briefs and Market Update) but has also been making a major statement in the OLED lighting market, with mass production commencing at its new Gen 5 OLED light-panel line in Gumi, Korea (Fig. 1), and the introduction of a new OLED light brand, Luflex. According to LG, the Gen 5 line (1,100 mm × 1,250 mm) has been producing about 15,000 sheets per month, an approximately 30-fold increase compared to the company's previous Gen 2 line (370 mm × 470 mm), with a monthly capacity of 4,000 sheets.¹

The company's new Luflex brand name is derived from "lux" (light in Latin) and "flexibility," reflecting OLED's flexible, bendable, and rollable characteristics. The OLED light panels are very slim (0.41 mm thick), and

their flexibility allows them to be fabricated in a variety of shapes, including curves or spirals (Fig. 2).

OLED lighting panels have already been adopted for experimental applications by world-famous

industrial designers including Ron Arad and Ross Lovegrove. LG Display has also started mass production of OLED tail lights for automobiles.

As a lighting source, OLED is considered to be easier on the eyes than conventional sources such as fluorescent and LED, as it offers great uniformity in its luminescence. It also exhibits very little temperature rise under normal conditions, meaning that it can be used to illuminate, for example, food displays or antique wooden furniture or buildings.

For the past five years, LG Display has hosted the international LG OLED Design Competition, a platform for designers



Fig. 1: LG Display's new Gen 5 OLED light-panel production line, located in its facility in Gumi, Korea, commenced operations in the fall of 2017.

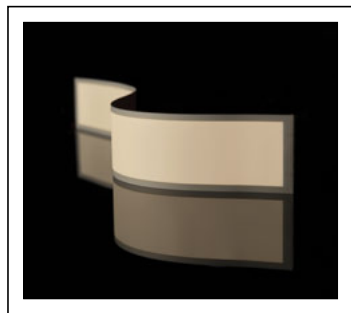


Fig. 2: LG Display has been placing additional resources behind the production of thin, flexible OLED lighting panels that can be used in a variety of architectural and artistic settings.

and architects to incorporate OLED lighting into their designs. The 2017 competition focused on creative uses for LG Display's 0.41-mm thick panels with a bending radius of 20 mm, and winners were announced in the categories of Lighting Design and Space Design.²

¹<http://www.lgoledlight.com/about-luflex/>

²<http://www.lgoledlight.com/design-competition-2017/>

Product Briefs . . .

The following represent a small sample of products that were scheduled at press time to be shown at CES:

Should there be any doubt that **LG DISPLAY** is firmly behind the future of OLED TV, that doubt should be dispelled with the company's announcement of its 88-in. 8K OLED display — the first of its kind, according to LG (Fig. 3). The company has revealed few details about the display, other than it has 33 million pixels (7,680 × 4,320) — four times more than UHD (3,840 × 2,160).



Fig. 3: LG Display's new 88-in. 8K OLED display incorporates 33 million pixels.

* * * *

The **VIDEO ELECTRONICS STANDARDS ASSOCIATION (VESA)** recently announced that DP8K Certified DisplayPort cables — native DisplayPort cables that are guaranteed to support DisplayPort High Bit Rate 3 (HBR3) — are on the market. HBR3 is the highest bit rate (8.1 gigabits per second (Gbps) per lane) supported by DisplayPort standard version 1.4, and provides the speed required to drive 8K video resolution at 60 frames per second (fps) using a single cable, as well as multiple 4K displays.

* * * *

In the augmented-reality arena are Vuzix Blade Smart Glasses from **VUZIX**, which won four International CES 2018 Innovation Awards prior to the show. Individuals can leave their phone in their pocket while the glasses present location-aware content from the phone. Retail and enterprise workers can use Vuzix Blade to scan barcodes, receive work instructions, take pictures, and use 2-way video streaming.

* * * *

SAMSUNG ELECTRONICS is adding to its signature curved display line-up with the debut of the new CJ791 monitor, the first curved monitor to feature Intel's Thunderbolt 3 connectivity. Designed for entertainment and business audiences, the 34-in. CJ791 model features a quantum-dot-enhanced LCD panel.

OLED TVs: Market Update

A recent report from IHS Markit noted that global shipments of OLED TVs grew 133 percent year over year (2016/2017), reaching a new monthly record of 270,000 units in November 2017. According to IHS, falling prices put 55-in. 4K OLED TVs into the budget range of a greater number of high-end holiday shoppers, with LG's lowest-tier OLED model priced at \$1,499.³

³<https://technology.ihs.com/Services/530849/tv-sets-intelligence-service-premium>

guest editorial



Lighting the Future

by Marina Kondakova

Lighting is an essential part of our lives. As solid-state lighting (SSL) technology advances, we expect that luminaires will become more than just illumination sources. Numerous research studies suggest that the lighting in our environment affects our productivity and alertness, and can influence our physical health and well-being. Lighting

affects performance and safety in industrial spaces. A recent study showed that improving the quality of light can help reduce risk in primary causes of occupational injuries.¹ The role of lighting is also increasing in the emerging areas of “smart” buildings and vehicles. Increased connectivity makes it possible to automate, monitor, and control all operational aspects of commercial buildings, for example. Lighting fixtures can include smart sensors and controls for the network for collecting data throughout the building.²

Presently, one of the most widely discussed topics of the effect of lighting on humans is circadian wellness. Our circadian rhythm is synchronized with the 24-hour cycle and triggered by natural periods of light and dark. The article by Dr. M. Figueiro, Director of Light and Health Programs at the Lighting Research Center (LRC), discusses differences in the way that light affects the circadian and visual systems. Because the circadian system responds to multiple factors, such as timing, duration, and amount of light exposure as well as spectral properties of the light, the design of circadian-healthy lighting requires different rules.³ The LRC recommends use of the circadian light (CL_A) and circadian stimulus (CS) metrics that characterize impact of light on human circadian systems to help designers create healthy lighting.

Dr. Figueiro presents the results of multiple studies on the effects of light exposure from self-luminous displays on melatonin suppression. Melatonin is a hormone produced by the human body that helps control the sleep-wake cycle.⁴ Disturbance of the cycle has detrimental effects on health. The studies conducted showed that exposure to short-wavelength blue light from device screens at night resulted in decrease of melatonin levels, especially in adolescent participants. However, properly controlled exposure to blue light during the daytime can increase alertness. Such exposure was used to improve the sleep and behavior of Alzheimer’s patients. Thus, the results presented in this paper contribute to our understanding of light’s impact on our well-being, and show that the new use of modern lighting can provide very significant benefits.

Rapid development of LED and, particularly organic LED (OLED) lighting technology has allowed for dramatic changes in form, scale, and application of luminaires. While a wide variety of commercial LED products have been available for a while, OLED lighting is just starting to enter the lighting market.

OLED offers a new perception of light; it provides pleasant, diffused illumination from a large surface rather than from a point source. The light is soft, casting no shadows or glare. Its quality is similar to natural sunlight. OLED panels enable new, creative lighting designs because they are extremely thin, lightweight, and capable of operating at temperatures near ambient. The panels can be made on flexible or rigid substrates.

In the article, “OLED Lighting Hits the Market,” OLEDWorks’ Business Development Director G. Phelan discusses various applications for OLED lighting and pro-

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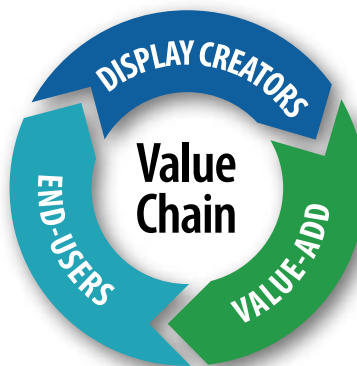
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Biological Effects of Light: Can Self-Luminous Displays Play a Role?

Light is the major synchronizer of circadian rhythms with local time on earth, and can also promote alertness in humans. Self-luminous displays built in a variety of form factors can be used to optimize circadian synchronization and alertness.

by Mariana G. Figueiro

HUMANS have a biological clock located in the brain's hypothalamus that generates and regulates circadian rhythms, which repeat in a cycle approximately every 24 hours. These rhythms include processes such as sleeping and waking, body temperature regulation, hormone production, and alertness. Light is the main input for synchronizing the biological clock to the solar day. If we are not exposed to a sufficient amount of light in the appropriate spectrum, for a sufficient amount of time, and at the right time, our biological clock becomes desynchronized with the solar day and we may experience disturbances in physiological functions, neurobehavioral performance, and sleep.^{1,2}

The circadian and homeostatic systems influence the sleep–wake cycle. Sleep homeostasis (*i.e.*, regulation of the need for sleep) increases with time awake, contributing to strong pressure to sleep at night. The circadian

system sends an alerting signal to the body during the day, counteracting the increase of sleep pressure with time spent awake, and sends a sleeping signal during the night, promoting a consolidated night of sleep. A person is more likely to experience a good night of sleep when the circadian and homeostatic systems are aligned. Misalignment between these two systems can also lead to health problems such as metabolic and cardiovascular diseases, depression, and cancer.

Another well-known circadian rhythm is the cyclical production of melatonin, a hormone that is produced by the pineal gland at night and under conditions of darkness. For diurnal species, such as humans, melatonin signals that it is time to sleep. The timing of the onset of melatonin secretion in the evening, referred to as dim light melatonin onset (DLMO), occurs approximately two hours prior to natural bedtimes and is used as a marker of the biological clock. Evening exposure to sufficient amounts of light will delay DLMO, thereby delaying sleep times.

Lighting Characteristics Affecting the Circadian System. The characteristics of light affecting the circadian system, as measured by acute melatonin suppression and phase shifting of DLMO, are different from those affecting the performance of visual tasks like reading a book. Unlike the visual system, which consistently responds to light at any time of day or night, the circadian system's

response varies according to the timing and duration of light exposure, one's personal history of such exposure, the light's spectral properties, and the amount or level of light received. After bedtime, for example, a warm-color nightlight delivering low levels of light will permit safe navigation without the need to increase room and hallway lighting, but will not suppress melatonin production. On the other hand, because humans are especially sensitive to short-wavelength (*e.g.*, 460 nm) “blue” light,^{3–5} exposure to high levels of such light in the middle of the night will stimulate the circadian system at a time when it should be providing cues for melatonin production and the maintenance of proper metabolic functioning.

Light's effects on the circadian system vary over the course of the 24-hour day. Morning light from any source habitually received after the trough of core body temperature, which tends to occur in the second half of the night, will advance the timing of the sleep cycle to come. Light received in the evening (*e.g.*, from self-luminous displays) prior to the trough of core body temperature will delay the onset of sleep.⁶

Our research has also shown that it is important to accurately measure light exposure over the 24-hour day, as opposed to taking just a “snapshot” measurement of light exposure at a specific place and time.^{7,8} The circadian system appears to keep track of light

Mariana G. Figueiro, Ph.D., is director of the Lighting Research Center (LRC) and Professor of Architecture at Rensselaer Polytechnic Institute in Troy, NY. Dr. Figueiro is well known for her research on the effects of light on human health, circadian photobiology, and lighting for older adults. Her research is regularly featured in national media including The New York Times, The Wall Street Journal, and Scientific American. She can be reached at figuem@rpi.edu.

exposure, and knowing an individual's history of light exposure over the past 24 hours can help determine the best light prescription for the next 24 hours.⁹ For this reason, a light treatment or intervention designed to promote earlier bedtimes should not be limited to providing exposure to blue light in the morning, but should instead control the total circadian light exposure during all waking hours.

Developing Circadian Light Metrics. Architectural lighting has traditionally been designed and specified primarily to meet the needs of the visual system, but it has become apparent that lighting design for the circadian system requires different metrics. To that end, the Lighting Research Center at Rensselaer Polytechnic Institute (LRC) has developed the circadian light (CL_A) and circadian stimulus (CS) metrics for characterizing both the spectral and absolute sensitivities of the human circadian system.^{10,11} These metrics are based upon fundamental knowledge of retinal physiology as well as the measured operating characteristics of circadian phototransduction (*i.e.*, the conversion of light into electrical signals received by the biological clock), from response threshold to saturation. The CL_A metric represents irradiance weighted by the spectral sensitivity of every retinal phototransduction mechanism that stimulates the biological clock, as measured by nocturnal melatonin suppression. The CS metric is a transformation of CL_A into relative units from 0.1 (the threshold for circadian system activation) to 0.7 (response saturation), and is directly proportional to nocturnal melatonin suppression after a one-hour exposure (10 to 70 percent). The units and quantities for these metrics have also been published.^{10–12}

The LRC has released an open-access CS calculator^a to help lighting professionals increase the potential for circadian-effective light exposure in designs for architectural spaces. Developed by LRC researchers, the calculator is designed to facilitate the calculation of CL_A and CS for several example light source spectra as well as for user-supplied light-source spectra. To obtain the CL_A and CS values for a given source, the user simply selects the supplied source and its spectral power distribution (*i.e.*, the radiant power emitted by a light source as a function of its spectral power distribution), or enters their

own unique source data, and then enters the illuminance value (in lux) measured at the eye.

Self-Luminous Displays and the Circadian System

The use of self-luminous displays in the evening and nighttime hours may deliver sufficient light to the eye to suppress melatonin and delay sleep times. In fact, many recent reports suggest that the use of self-luminous displays before bed curtails sleep duration. We have completed three laboratory studies and one field study investigating the significant impact of various self-luminous displays on melatonin suppression.

Potential Detrimental Effects of Light from Self-Luminous Displays. The three lab studies followed a broadly similar protocol involving three or four experimental conditions while viewing cathode ray tube (CRT) computer monitors,¹³ tablet computers,¹⁴ and LED-backlit LCD flat-panel TVs¹⁵ over periods ranging from 90 minutes (TVs) to two hours (monitors and tablets) on each night of the study (separated by at least one week). Salivary melatonin samples were taken from participants at the beginning, midpoint, and conclusion of each experimental session. In the CRT monitor and tablet studies, the participants viewed the devices: (1) alone without an intervention, (2) while wearing orange-tinted glasses that filtered out optical radiation approximately <525 nm, and (3) while wearing goggles equipped with blue LEDs that directed 40 lux of 470-nm or 475-nm light at the participants' eyes. For the TV experiment, participants wore orange-tinted glasses on one night and viewed the same TVs set at progressively increasing correlated color temperatures (CCTs) (2,700 K, 6,500 K, and 12,000 K) on the remaining three successive nights of the study.

As our researchers expected for the CRT monitor and tablet experiments, exposure to the blue-light goggles significantly suppressed melatonin. Also as expected, viewing both devices without the orange-tinted glasses also suppressed melatonin. A one-hour viewing of the CRT monitor suppressed melatonin by a median value of 11 percent. Consistent with the CS model's predictions, suppression levels after a one-hour exposure to the tablets-only condition were not statistically different from zero. This difference reached significance after two hours, however, with an average melatonin suppression of 22 percent. The TV

experiment showed that sitting six or nine feet from the device resulted in no significant suppression of melatonin after a 90-minute exposure, irrespective of the device's CCT setting, compared to the orange-tinted glasses control.

Using a protocol adapted from the lab studies, we collaborated with a high school student researcher to collect field data on the effects of self-luminous displays on melatonin suppression in high school students (aged 15–17 years) during the evening.¹⁶ On two separate nights, the participants viewed their personal devices with and without orange-tinted glasses while also wearing a Daysimeter,¹⁷ a device that measures personal light exposures and rest–activity levels, from the time they woke that day until the end of that night's data collection period. They also collected saliva samples at hourly intervals during the three-hour data collection period. On the first night, the participants wore the orange-tinted glasses for the entire three-hour data collection period. On the second study night, they wore the orange-tinted glasses only during the first hour, and then viewed their personal devices without the orange-tinted glasses during the remaining two hours of the data collection period.

Compared to when participants wore the orange-tinted glasses, viewing their devices without the glasses resulted in mean melatonin suppression of 23 percent after one hour and 38 percent after a two-hour exposure. The Daysimeters, however, indicated that the participants received extremely low circadian stimulus ($CS = 0.01$, equivalent to a 1 percent predicted melatonin suppression) during the experiment. By comparison, mean melatonin suppression among the college students (mean \pm SD age = 28 ± 9.9 years) who wore Daysimeters during the CRT monitor lab study was 16 percent after a one-hour exposure that exposed them to a mean CS of 0.19, which is a log unit greater than that recorded for the adolescents. These data suggest that adolescents are much more sensitive to acute melatonin suppression from light in the evening than college students.

Potential Beneficial Effects of Light from Self-Luminous Displays. Light from self-luminous displays, if provided at sufficient levels and delivered at the right time, can benefit outcomes of sleep and mood. Alzheimer's disease patients, for example, suffer from conditions such as disrupted sleep,

^a<http://www.lrc.rpi.edu/programs/lightHealth/index.asp>

depression, and agitated behavior. Some of these problems are associated with age-related changes to the eye that permit less light (especially short-wavelength light) to reach the retinae, thereby reducing input to the biological clock. Alzheimer's disease patients can also experience neuronal degeneration that reduces the biological clock's sensitivity to light, and the situation is worsened by the dim, constantly energized lighted environment typical of nursing homes and assisted-living facilities.

Our research has demonstrated that self-luminous tables can be used to improve sleep, behavior, and mood in Alzheimer's disease patients.¹⁸ While our previous research had shown that a robust 24-hour pattern of light and dark improves sleep, while also reducing depression and agitation in this population,^{19,20} a major challenge remained in delivering light to patients' eyes. Given that it is common practice in these facilities to gather residents in a common area during the day, frequently in groups around tables, we hypothesized that a practical way to deliver the light would be to install LED lighting in those tables (Fig. 1). In a pilot study, we worked with Sharp Corp. to build tables incorporating 70-in. LED edge-lit LCD TVs that delivered a large amount of CS by providing 2,000 lx of 25,000 K light at the eye.

In the facility where we conducted this research, residents typically had their meals and remained seated at the light tables for the entire day in a room that provided no direct access to daylight. The tables were programmed to operate from 7:00 am to 6:00 pm. Baseline data were collected during the first study week, and the residents experienced the daily light exposure for four weeks. Post-intervention data were collected at the beginning of the fourth week. The study's outcome measures included objective (actigraphy) and subjective sleep (Pittsburgh Sleep Quality Index [PSQI]),²¹ depression (Cornell Scale for Depression in Dementia [CSDD]),²² and agitation (Cohen-Mansfield Agitation Index [CMAI])²³ scores. Results from the six residents participating in the experiment showed a significant improvement in sleep quality and a reduction in depression and agitation scores. Data collection using additional experimental participants is under way.

Can Displays Play a Role in Light and Health?

Lighting systems using color-tunable LEDs are now widely available on the market, and



Fig. 1: A light table used to deliver circadian-effective light to Alzheimer's disease patients in a nursing home is shown with the author.

are typically installed in ceilings to deliver direct, direct-indirect, or indirect light into the space. As light needs to reach the back of the eye to support the circadian system, however, and ceiling lights are not always ideal for accomplishing that, we have found that self-

luminous displays can more practically and effectively deliver circadian light to users' eyes. Effective form factors include light tables (see Fig. 1) and vertical displays attached to walls or office cubicle partitions (Fig. 2), both of which could also be used to

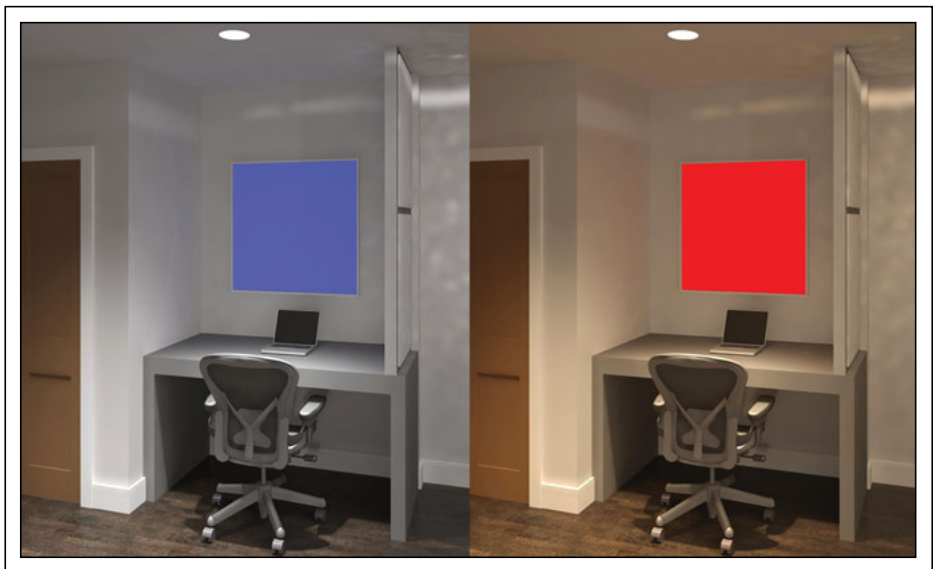


Fig. 2: These renderings show how self-luminous displays might be used to deliver circadian effective (blue) or circadian ineffective (red) light in light oases, depending on time of day.



Fig. 3: Personal light-therapy goggles delivering red light can be used to promote alertness in the afternoon and evening without disrupting the circadian phase. Blue-light goggles may also be used early in the day to promote circadian entrainment.

deliver information, or personal light therapy goggles (Fig. 3). The light table used in the Alzheimer's disease study, for example, could also function as a touch screen that displays games or entertainment to attract attention and ensure that light is reaching the back of the recipients' eyes. We are presently developing personal light sensors that can provide a prescription for when to deliver, and when not to deliver, circadian-effective light to individual users. These sensors can then communicate wirelessly with the self-luminous displays to ensure that the appropriate light is being delivered at the right time.

Potential Impact of Research

Light-dark patterns received at the back of the eye are the major synchronizers of the biological clock to the local time on Earth. Self-luminous displays can be designed and used to practically and effectively deliver light to promote circadian entrainment or deliver an alerting stimulus without affecting circadian phase. Taking into account that the timing of exposure also needs to be considered, new sensors that are now being developed can

determine the appropriate time for delivery of the prescribed light. Manufacturers are invited to use the open-access CS calculator to identify the optimum spectrum and light level needed to successfully deliver the desired circadian-effective light. These are exciting times, and self-luminous displays can play an important role in delivering the right light at the right time to promote health and well-being among all age groups.

What Can Developers and Display Engineers Do Now?

A crucial next step in advancing display technologies for circadian health is for developers and engineers to rigorously quantify the effects of all new applications and devices. Several applications for promoting circadian entrainment or reducing circadian disruption among users of self-luminous displays have come to market over the past several years, for example, but to date their effectiveness remains unproven at best.

The LRC recently investigated one of these applications, Apple Inc.'s Night Shift, which offers users display adjustment options ranging from a "less warm" (high CCT, 5997 K as measured via spectrometer) setting to a "more warm" (low CCT, 2837 K as measured via spectrometer) setting, the latter being designed to minimize stimulation of the circadian system. Night Shift also offers a time setting, which activates the low-CCT display mode at a user-defined interval before bedtime in accordance with proven sleep hygiene principles. Our study involving 12 young adult participants who viewed iPads between 10:30 pm and 1:00 am, however, found no significant difference between the two modes in terms of acute melatonin suppression when the device was set to full brightness.²⁴ We concluded that regardless of Night Shift setting, selecting low light levels, limiting device use to one-hour sessions, and avoiding displays at least two hours before bedtime would be more effective for reducing nighttime CS exposures.

Use of the CL_A and CS metrics could help to avoid these pitfalls and provide prospective users with products that are proven to deliver what is promised, and far more importantly, what is urgently needed in our around-the-clock lighted environment. Unfortunately, at least for anyone who might be interested in an easy solution, beyond these metrics and sound scientific practice there exists no tried and

true formula for success other than continued research and development. For only then will we see devices that strike an optimal balance between CS exposure and factors that are very important for user satisfaction and device appeal, such as color rendering. By quantifying CS and using the data to design innovative products that can do things like track exposure and deliver personalized, 24-hour lighting prescriptions, we will then be able to provide users with devices that are great to use while also being better for them.

Acknowledgments

The author would like to acknowledge Sharp Laboratories of America, which funded the self-luminous displays studies, and the National Institute on Aging (R01AG034157), which funded the Alzheimer's disease studies. The author would also like to thank David Pedler for his technical and editorial assistance.

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(continued on page 20)

OLED Lighting Hits the Market

Performance and design freedom are advancing organic light-emitting diode (OLED) lighting, providing differentiation from general lighting to transportation and more. OLED is the first naturally diffuse lighting, with pure qualities highly prized by designers. Razor thin with superb color characteristics and uniformity, OLED offers an alternative to high-glare lighting sources and allows a variety of innovative applications and attractive designs.

by Giana M. Phelan

AS a solid-state lighting (SSL) technology, OLED has many of the attributes of its elder cousin, LED. It is mercury free, compatible with standard control and dimming solutions, and requires direct current (DC) power. The promise of OLED has been heralded for some time, but recent technology gains have been achieved at a relatively breakneck speed. For example, LEDs were demonstrated as a practical component in 1962, while OLEDs were first demonstrated in 1987. With OLED light engines now at 60 to 80 lumens per watt (LPW), OLED has arrived for many applications.

Furthermore, as shown in Fig. 1, the price of OLED lighting continues to fall as performance increases. This combination of affordability and performance is moving OLED lighting into mainstream applications. The ability to efficiently integrate controls into SSL systems is a significant contributor

to energy savings for lighting. In 2016, lighting accounted for 11 percent of energy consumption in the commercial sector, down substantially from 25 percent in 2006, and directly attributable to SSL lighting products combined with controls.^{1,2}

OLED lighting has benefited from the investment in OLED displays, particularly

with regard to new materials and supply scale. In addition, OLED awareness has exploded – everyone knows that the latest iPhone (iPhone X) has an OLED display. However, OLED lighting has several performance and cost challenges that are surprisingly more demanding than for displays. These challenges range from higher luminance levels (8× to 20× that

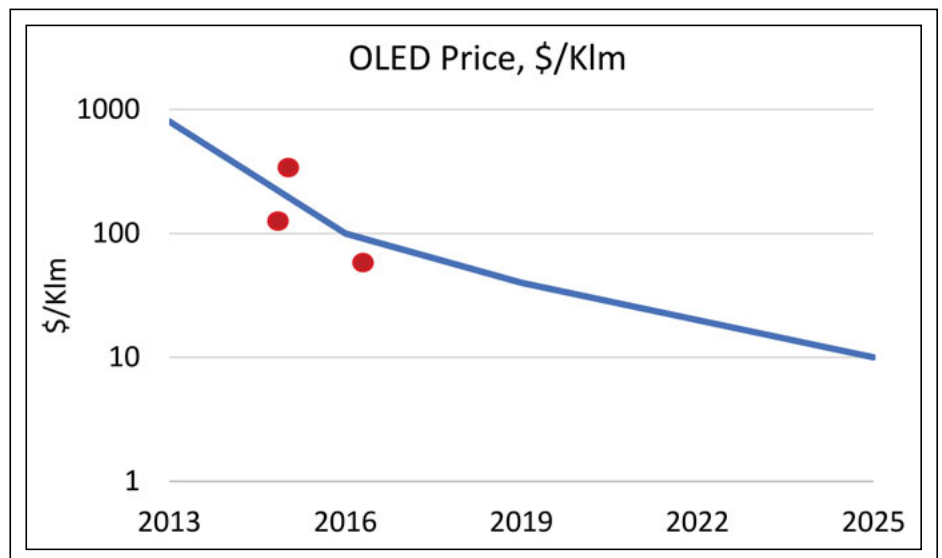


Fig. 1: Pricing, in terms of \$/klm, will decrease for OLED solid-state lighting through at least 2025, according to the Department of Energy's 2014 SSL R&D Manufacturing Roadmap.³ klm = kilolumens or thousands of lumens.

Giana Phelan is currently director of business development at OLEDWorks LLC, an OLED lighting technology and manufacturing company, where she leverages her extensive experience in microelectronic systems, collaborating with luminaire designers, furniture makers, automobile manufacturers, contractors, and architects, to accelerate OLED lighting adoption. She can be reached at GPhelan@oledworks.com.

of information displays) to longer lifetime requirements (10 years) and markedly different cost points. It is difficult to imagine people spending \$110 on a 4-in. OLED light the way they do for the display on an iPhone.⁴

Displays operate primarily in video mode with subpixels on the micron range; a missing subpixel due to a short is generally not detected by the human eye. For lighting, a short will cause a large, noticeable dark spot and may ultimately cause the entire light panel, a single large pixel, to fail. The reliability demands are not just for hard fails; lighting panels are usually used in clusters and must accurately match on white color point when installed and as they age. These challenges are rarely constraints for displays.

Industry Overview

OLED Light-Panel Manufacturers: A summary of the primary participants in the OLED panel-production industry appears in Fig. 2. This snapshot captures several strategic elements from the past two years. In 2015, New York-based OLEDWorks (the author’s company) acquired Philips’ key OLED assets, effectively merging expertise from Philips and the Eastman Kodak company while establishing complementary manufacturing in two regions. That same year, LG OLED lighting was acquired by LG Display from LG Chem. This was followed shortly by an announcement that LG lighting panels would be mass produced on fifth-generation manufacturing

technology. Earlier in 2017, Konica Minolta, which had been focusing on solution-based OLED on plastic substrates, announced a new joint venture company with Pioneer. Osram’s singular focus on the automotive market has been rewarded with industry-leading products, beginning with tail lights in the Audi TT.⁵

While lagging LED on efficacy, OLED panels now meet the performance threshold for many applications. OLEDWorks produces panels with high luminance capability, opening the application space for this technology. Even at the high-luminance output, about 3× to 4× that of competitive panels, the panels are low glare and provide a very comfortable and welcoming light experience. LG Display’s catalog features 90 LPW (3,000K) panels in a large variety of shapes.⁶ Three types of flexible panels with efficacies of 52 to 55 LPW are included in the catalog of products as well. Cost-effective flexible lighting panels with high performance will be critical for differentiating OLED from LED and further acceleration of the OLED lighting market.

Lighting Market Segments: The OLED light panel, with its simplicity of integration, blurs the line between light engine and fixture. This duality is reflected in the broad range of applications. With 24V DC wiring, the panels can be mounted directly onto ceilings, walls, and shelving (Fig. 3). With their low profile, the panels are almost flush to the surface, while simultaneously not requiring a deep plenum for hiding heat sinks or other packag-

ing required by LEDs. Architectural and large-scale projects were among the initial applications for OLED. When first commercially viable, OLEDs were still limited in light output but commanded a premium. However, the beauty of the light quality positioned OLED to make a statement and to create a unique ambience.

Astron-Fiamm, a Swiss lighting company, sells its Paris-based Blackbody I.RAIN platform in both commercial and residential markets, with products that create a wash of soft light. In Europe, grand installations by iart (a Swiss company that specializes in lighting and media architecture) and the German industrial firm Hatec (Fig. 4) use the brighter OLEDs from OLEDWorks. Generally, these installations feature programmable patterns that create movement and are designed to invite people into a space.

With increasing panel performance and declining costs, OLED has gained traction in more traditional general lighting applications. Fixtures range from single-panel desk lamps and sconces to multi-panel suspensions with utility in residential, commercial, retail, and hospitality settings. High-luminance panels break the paradigm that OLED soft lighting is also dim lighting – users see the light as soft, yet bright and functional. A comprehensive study of high-luminance OLED in a commercial application was completed by the US Department of Energy (DOE). This study will be discussed later.

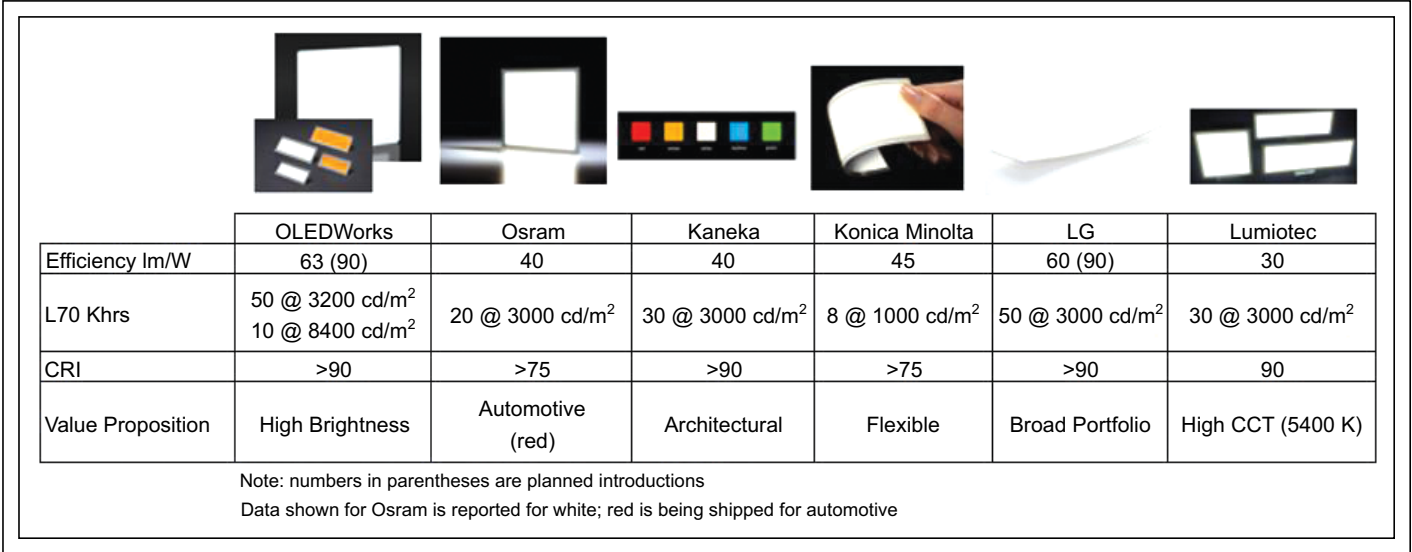


Fig. 2: An OLED lighting industry snapshot for white light shows technical advances for six companies.

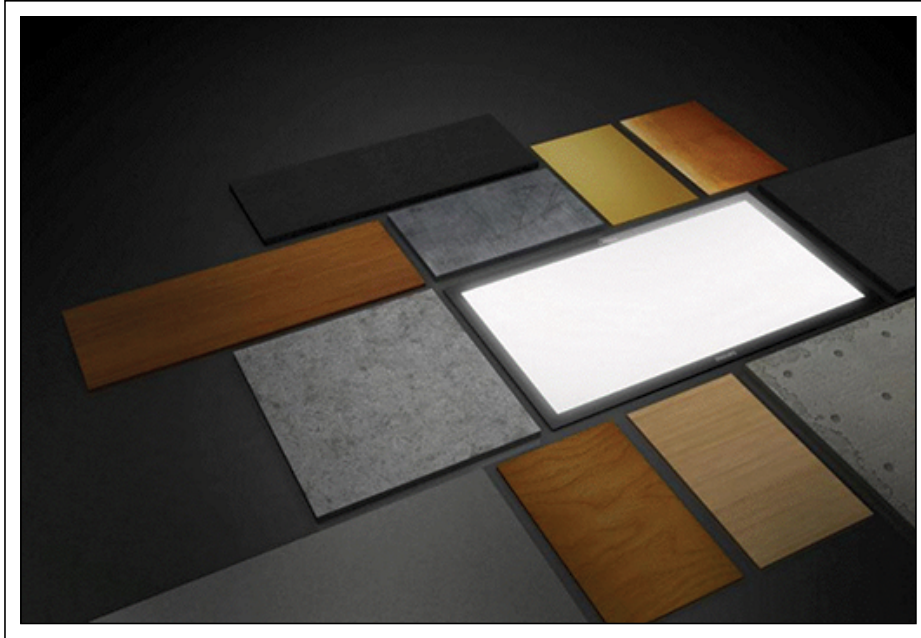


Fig. 3: OLED panels can serve as slim and flexible building materials.

The transportation industry, including automotive, aero, and railroad segments, is exploring how the combination of extreme light weight, thin profile, and light uniformity can provide benefits. This includes interior as well as exterior (tail lights, *etc.*) lighting. At InnoTrans, a European international transportation trade show, architect and designer Andreas Vogler recently debuted a passenger railroad car design, AeroLiner3000 (Fig. 5).⁷

Design Differentiation

OLEDs eliminate many components essential for other lighting technologies. Heat sinks are not needed, yet the OLED remains relatively cool to the touch (due primarily to the very large relative surface area of the emitter). Light output is full spectrum and uniform without light guiding, mixing, diffusing, or reflecting. With little to no glare, OLEDs do not require shades or a way to hide the panel – the light source can be embraced in direct view.

Efficiency: The efficiency of OLED light panels continues to improve, with new products at 80 and 90 LPW entering the market. Over 100 LPW is within sight, just a few years down the road.

These gains are achieved through progress made with OLED materials and device formulation. The increased efficiency is also

realized through novel technology for light extraction, reducing the loss of light trapped in the system. Harvesting the light generated into usable light lifts panel efficiency on the order of 40 percent or more. The light-extrac-

tion technology also manages the wavelength consistency as measured off angle from normal. It is important to ensure that the light trapped does not result in poor color uniformity.

When designing a space with OLED lighting panels, application efficiency can make OLED solutions very competitive. Application efficiency deploys design elements that allow the light to be close to users and more intimate with the space being lit so that the light falls where it is wanted. The direct-view nature of OLED allows, even promotes, designs with high efficiency. They don't require designers to keep hot elements from users, or to hide large, bulky heat sinks, or to keep a light source remote due to glare. Application efficiency analysis has been reported by Acuity Brands Lighting suggesting that OLED solutions can be even more efficient than LED.⁸

Thin and Cool: The thin profile of the OLED is certainly eye-catching. The fact that it can remain thin, without the baggage of heat sinks, encourages creative thinking. Moreover, the low temperature of OLEDs, which is less than 40C even at high luminance levels, creates a canvas for a broad swath of materials ranging from wood to textiles to plastics. Marrying light with unique materials

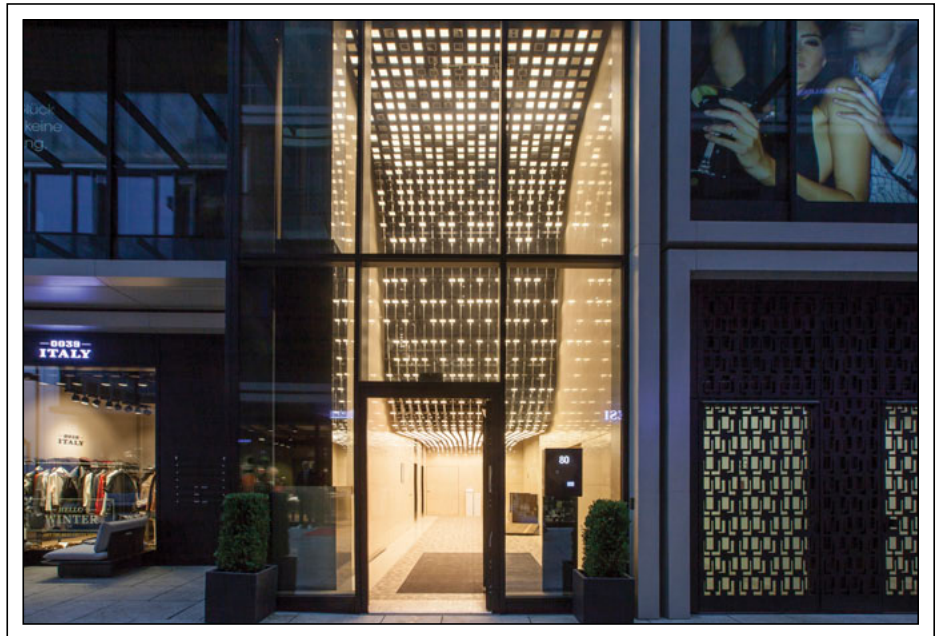


Fig. 4: An OLED installation by Hatec can be seen on Neue Mainzer Strasse in Frankfurt, Germany. Image courtesy Hatec.

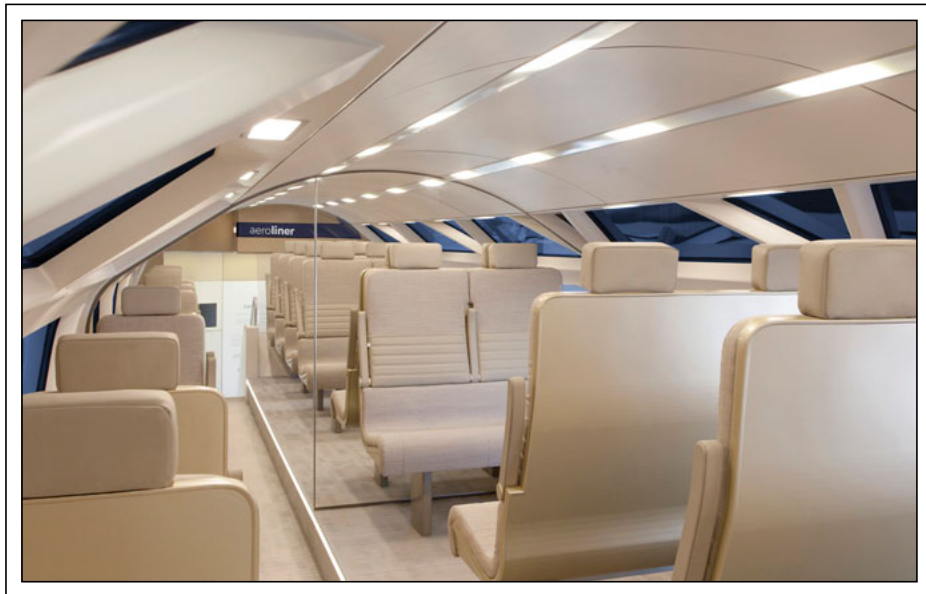


Fig. 5: This interior for an AeroLiner3000 railroad car features OLED lighting in a design by Andreas Vogler. Image courtesy A. Vogler.

enriches the brand opportunity for many designers as well as the experience of the end user.

Drivers and Power: OLED driver-panel simplicity does have some design challenges. In many cases, the driver needs to be small, not adding bulk to an otherwise streamlined presentation. LED drivers are not typically designed for the low-current demand of OLEDs – 100 mA to 300 mA is common – and therefore tend to be inefficient contributors, often cutting efficiency as much as 30 percent. Also, LED drivers do not have short-circuit protection, which shuts off power should an electrical short be detected in the OLED. Both limitations are overcome by using drivers specifically designed for OLEDs; efficiency >90 percent is available.

OLEDs are low-voltage (DC) components, either 12 VDC or 24 VDC. Low voltage allows for several options for integration into a structure. One option that is growing in popularity is having the AC/DC power conversion done remotely and running 24 VDC cables to the fixtures, usually with integrated drivers. This is an inexpensive and safe way to power the OLEDs. Other solutions include using direct-to-wall power drivers that convert the AC input to the 24 VDC needed.

Standard dimming controls are used with the OLEDs, including 0 to 10 V protocol and

pulse-width modulation (PWM). The former is more common.

When specifying power demands for OLEDs, it is important to note that the device voltage changes with temperature and operating time. As depicted in Fig. 6, over the life of an OLED, there is an increase in voltage that occurs due to aging. So as the voltage naturally increases (at constant current), the overall efficiency is somewhat reduced and fewer lumens are generated. These results are reported by each manufacturer as the L70 lifetime (Fig. 6), with voltage increasing 0.5 V to 1.5 V depending on the panel and usage. At lower temperatures, the panels also show a small voltage increase; this is relevant for applications such as refrigerators.

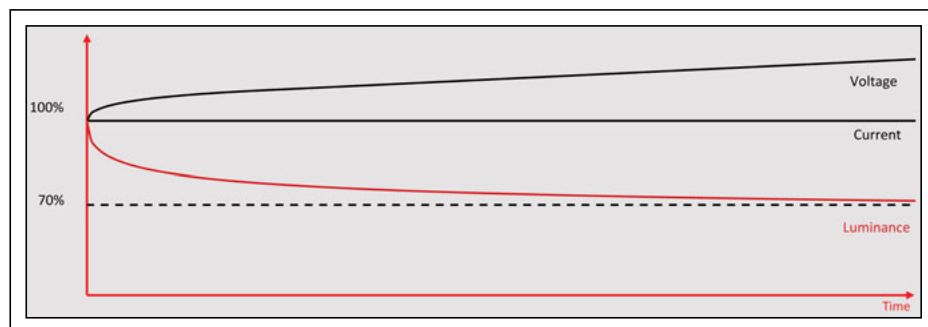


Fig. 6: Voltage rises with aging.⁹

Well-Being: White OLEDs are broad spectrum lights. They emit the wavelengths required and as determined by the choice of OLED emitters. Unlike LEDs, OLEDs do not need phosphor coatings – wavelengths are not down-converted through phosphors to try to capture a wider color gamut.

The DOE's Pacific Northwest National Laboratory (PNNL) has published a new way to look at the color rendering of light sources.¹⁰ This tool, TM-30-15, depicts a more complete color space and does not rely on discrete color patches as used in the standard Color Rendering Index (CRI). The TM-30 is useful for seeing how well a light source captures colors between the CRI reference patches. Not all CRI > 90 light sources will do more than recreate the color of the reference patches, losing color fidelity where not typically measured. Figure 7 shows the TM-30-15 output for the OLEDWorks Lumi-blade Brite 2 panel, with CRI > 90.

The Seoul National Library has adopted LG OLED for table lights, stating that they were taking advantage of spectral output that does not harm the eyes or the skin.¹¹ OLEDs, including the high-luminance panels from OLEDWorks, consistently measure in the exempt, or no-risk, category for IES 62471 testing on photobiological risks. Combined with excellent color rendering and low glare, OLEDs offer significant features for architects and building owners considering occupant well-being as a priority.

Amber OLEDs have a unique niche in the health segment. Because OLEDs are not a phosphor conversion system, there is no need for any blue in the amber spectrum. Therefore, amber provides a light that is not only high efficiency but promotes healthy sleeping patterns and safeguards circadian rhythms.

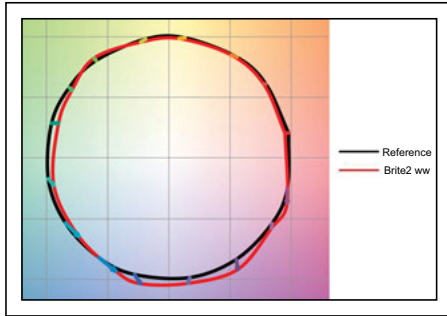


Fig. 7: The TM-30-15 OLEDWorks Brite 2 3,000 K is a warm white OLED. Above is a sample TM-30 analysis that shows the color properties of the source vs. the reference for the 3,000 K white point. The overlapping of the source and reference clearly shows where the reference is saturated or desaturated as compared to the source. Image courtesy OLEDWorks.

DOE Gateway Study – OLEDs in Practice

In September 2016, the accounting firm of DeJoy, Knauf & Blood (DKB) relocated its offices in Rochester, New York. The firm had been housed in a 100-year-old building with a

1970s “rabbit warren” cubicle layout with low ceilings and fluorescent T8 lighting. In the new location, DKB wanted a modern office layout with solid-state lighting solutions – a combination of OLED and LED lighting. The OLED fixtures are predominantly in shared spaces with limited natural lighting. The LEDs run across an open work area that is complemented by large windows on three sides.

This space was studied as a DOE Gateway project, with a report authored by Naomi Miller of PNNL.¹² Gateway studies are a third-party, nonbiased activity in which the lighting quality, performance, and overall experience are reported. The DOE has issued numerous LED Gateway reports to educate end users, decision makers, municipalities, and others about new lighting technology and progress. The DOE does not pay for any of the fixtures or installations. It only reports on the implementation experience.

The DKB site is the second Gateway OLED study and considerably larger in scale than its predecessor. All lighting fixtures used at DKB are commercially available. The report concludes very favorably on the OLED experience, both quantitatively and qualitatively. Quantitatively, the OLED fixtures

ranged from 27 LPW to 80 LPW. The former has the first generation of Lumiblade Brite panels combined with a low-efficiency driver solution – it is a very elegant fixture. The latter is from Acuity Brands and combines the higher performing second-generation Lumiblade Brite 2 panels for down lighting, with LED up lighting in a hybrid package. Selected commercially available fixtures are shown in Fig. 8.

Other products used extensively in the DKB site include the Visa Lighting Petal and Limit suspension fixtures, as well as Acuity Brands’ Lighting Trilia. The OLED panels operate between 5500 cd/m² and 8300 cd/m², which is significantly higher than the standard OLED panels previously available with a maximum output of 3000 cd/m². At high luminance, a concern was glare. However, the study concluded that glare was not a factor for the OLEDs but did continue to be an issue for the LED downlights used in the DKB space.

Amber lighting is uniquely featured in the “mother’s room” at DKB. Although LED downlights are also available, occupants use only the amber to avoid glare and discomfort. It has been reported that people with migraines also use this room to relax and manage their condition. Since the Gateway report was released, DKB has replaced one hallway of LED downlights with surface-mount OLED tiles to eliminate glare in that space.

The Spread of OLED Lighting

OLED lighting has made great progress in a short amount of time and is now a viable solution for illuminating spaces. Its low glare, natural diffusion, and high light quality allow for an excellent user experience. As costs continue to drop and performance continues to rise, OLED’s unique properties will increasingly illuminate your space.

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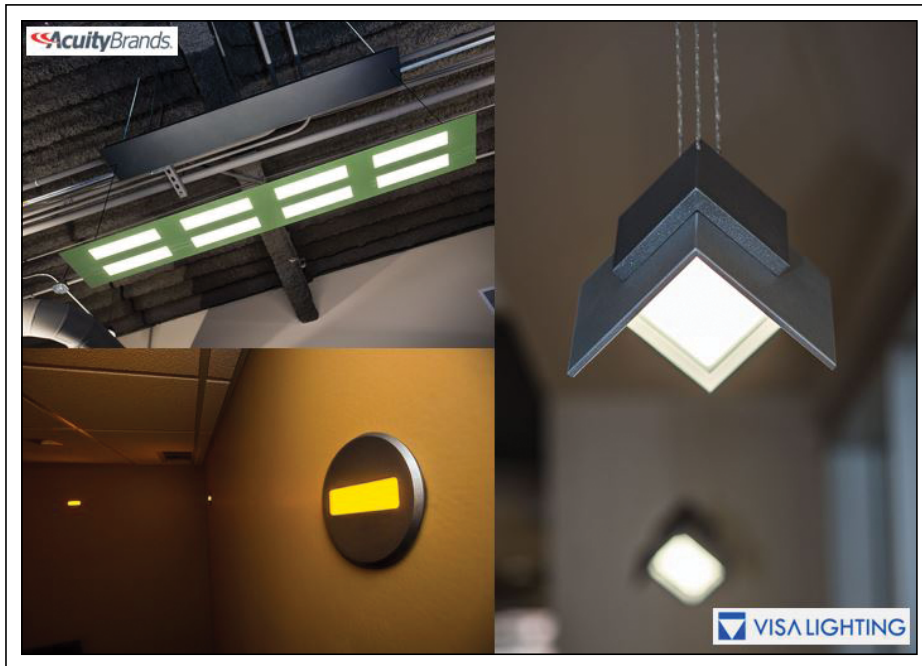


Fig. 8: Lighting technology from Visa Lighting Petal, Acuity Brands Olessence, and Amber Marker was used in the DKB installation. Image courtesy DeJoy, Knauf & Blood, LLP.

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guest editorial

continued from page 4

vides an overview of commercially available products. The author points out that OLED's unique form factors, such as thinness, lightness, and flexibility, will be key differentiators from LED lighting systems. OLED lighting products are currently higher priced than those based on LEDs. However, as their performance is continually improving and costs are decreasing, OLED has become a viable component of lighting technology.

The articles featured in this issue describe the latest trends in the development of lighting technology. The role of lighting is changing as we continue learning about its additional functionalities, including its effects on people and the environment.

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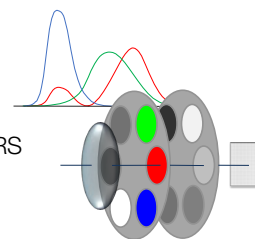
WHEN PERFECTION IS THE EXPECTATION

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High-Resolution LCD Headlamps for Intelligent Lighting

Vehicle headlamps that adapt to external conditions are established and available in mass-production vehicles; now the market is requesting headlamp systems with increasing resolution. Active-matrix LCD (AMLCD) with amorphous silicon thin-film transistors (a-Si TFTs) is a mature and cost-efficient technology that is known for its reproducible and homogeneous performance. Integrating an AMLCD with a-Si TFTs into an LED-based headlamp can fulfill all specifications for realizing a fully adaptive headlamp setup with high resolution.

by Christiane Reinert-Weiss and David Duhme

SINCE the first candlelit headlamps were mounted on horse-drawn carriages, lighting technology has evolved alongside the vehicles in which it is installed. From acetylene gas lamps in the late 1880s to xenon headlamps in the 1990s, lighting modules improved in efficiency but remained analog. The implementation of adaptive systems in modern vehicles creates a new performance demand on headlamps that traditional analog technologies

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cannot fulfill. Whereas traditional analog headlamps simply illuminate their environment with a predefined light distribution, the new digital systems react to the environment and require that the headlamps dynamically adjust their beam patterns appropriately. To be able to do this, the headlamp system uses data like speed, steering angle, GPS, and ambient data provided by sensors and cameras already integrated in modern vehicles. Based on this data set, methods like object recognition calculate an optimal adapted-lighting distribution, which is then projected onto the street in real time. Apart from dynamic bend lighting, which improves illumination during cornering, the glare-free high beam is the most prominent feature implemented in state-of-the-art headlamps (see Fig. 1).

The era of intelligent headlights in series-production vehicles began with the “High Beam Assistant” introduced by BMW in 2005, which automatically turned off the xenon-based high beam when oncoming traffic was detected. Mercedes followed with its “Adaptive High Beam Assist” in 2009, which adapted the range of the low beam automatically, and VW introduced its “Glare Free High

Beam” in 2010, using rotating drums to create vertical cut-off lines. The latter two systems both use a xenon light source. The first matrix LED headlamp acting as a solid-state technology for glare-free high beams was introduced by Audi in 2013.

From an automated “on” and “off” to constantly adapting beam patterns, each consecutive generation of adaptive headlamp modules increased the number of realizable functionalities to improve both safety and convenience for the driver. Today’s headlamps can create arbitrary light distributions like de-glaring other traffic or reducing the illumination of reflective traffic signs to avoid self-glaring while keeping the surroundings fully illuminated. To accomplish this, the headlamp modules divide the illuminated area in front of the vehicle into a grid of small segments with individually controlled light intensity. The higher the resolution of this grid, the better the realizable lighting functions. A state-of-the-art adaptive LED-matrix technology is represented by the “Multi Beam LED” implemented by Mercedes Benz in 2016, which divides the area in front of the vehicle into 84 light segments.

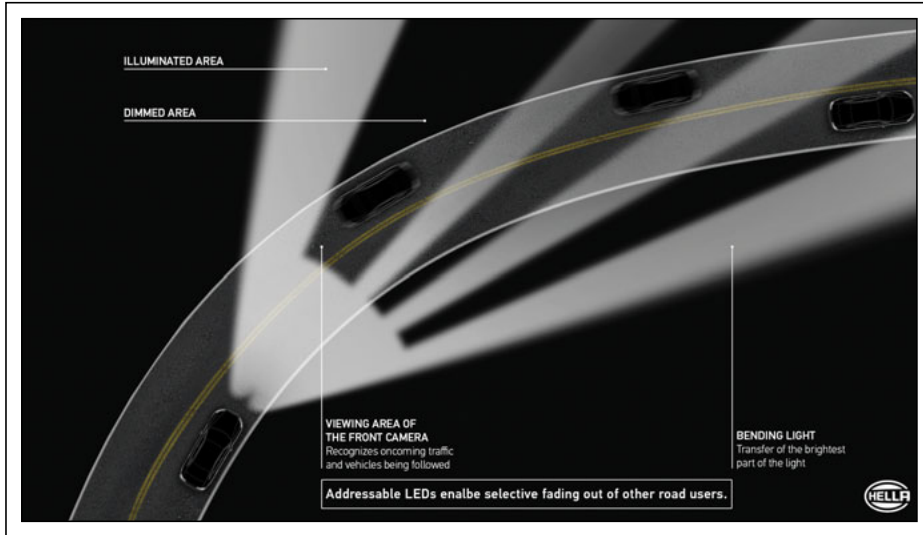


Fig. 1: The above illustration shows a car with adaptive headlamps employing a glare-free high beam. Source: HELLA GmbH & Co. KGaA.

Digital Light: Current Technologies

The above description of an adaptive headlamp very much resembles the description of an active-matrix liquid-crystal display (AMLCD). The active matrix is a grid of pixels, and the amount of light passing through each pixel is actively controlled by drivers. But can an AMLCD headlamp compete with state-of-the-art technologies? At the moment, the three other main technologies³ that are being investigated and implemented in the search for higher resolution and optimized functionality are:

μAFS (Micro Adaptive Frontlight System):

By increasing the number of LEDs on a single chip to 1,024, headlights with ≥ 1 K individually controllable pixels each can be realized.

DMD (Digital Mirror Device):

A strong LED light source illuminates a chip with >500 K micro-mirrors.

Laser Scanner:

A laser beam is directed via a mirror onto a phosphorous plate to create arbitrary lighting distributions.

Regardless of the method used to create a high resolution, all of the systems mentioned need additional optics to create the desired

light distributions. Compared to these technologies, an AMLCD headlamp can not only similarly fulfill the requirements of a headlamp application, but provide distinctive advantages to be considered for further investigation.

Advantages of an AMLCD Headlamp with LED Matrix

In a headlamp using matrix LEDs alone, like the “Multi Beam LED” from Mercedes Benz mentioned earlier, or the μ AFS, the number of pixels equals the number of LEDs implemented in the matrix. Therefore, the number of achievable pixels is limited by the number of LEDs one can operate within the limited installation space of a headlamp or integrate on one chip. Both approaches therefore result in a limited resolution. By combining an LED-matrix backlight with an AMLCD module, the number of individually addressable pixels can be increased to tens of thousands while at the same time decreasing the number of required LEDs substantially. The LED matrix for the AMLCD headlamp developed by the authors’ team,¹ as described below, consists of only 25 LEDs. The electronic control unit (ECU) can drive the LEDs at a maximum of 3 amps. For a high-beam light distribution, the LCD module consumes 75 watts.

In contrast to DMDs or laser scanning, an AMLCD headlamp does not need movable mirrors or other mechanical elements. AMLCDs are already mass produced for flat screens and are available at low cost.

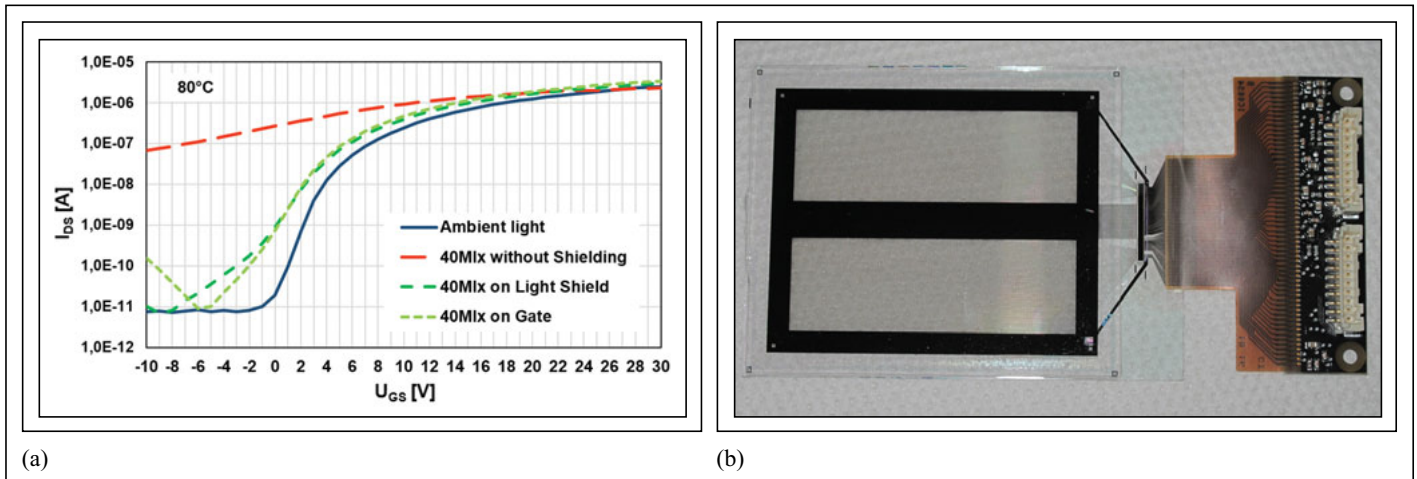


Fig. 2: At left (a) appear typical input characteristics of a-Si TFTs under different lighting conditions and at right (b), a bonded TN AMLCD with an a-Si TFT backplane. Source: IGM, University of Stuttgart.

For these reasons, the Institute for Large Area Microelectronics (IGM or Institut für Großflächige Mikroelektronik) at the University of Stuttgart and HELLA GmbH & Co. KGaA investigated the feasibility of an LED-based AMLCD headlamp as part of the BMBF (Bundesministerium für Bildung und Forschung, German Federal Ministry of Education and Research) project VoLiFa2020.²

Development of an LED-Based AMLCD Headlamp

When considered against the many possible combinations of light sources and light-distribution mechanisms, LED-array background lighting with an AMLCD module offers many advantages. LED matrix is a technology already used as a light source in headlamps, as mentioned above. In addition to LED technology's well-known benefits, such as compactness and energy efficiency, its highly adaptable light spectrum makes it an ideal light source for AMLCD modules. Halogen and xenon lamps both have light spectra with a UV portion. As the organic components of an LC display, particularly the liquid-crystal composition, degrade under UV illumination, choosing a well-adapted light source increases the lifetime of the system significantly. White high-power LEDs such as phosphor-coated GaN LEDs are able to provide a sufficient luminous intensity and the necessary UV-free light spectrum for a durable AMLCD headlamp.

But integrating an AMLCD-module into a headlamp raises problems, the most substantial of which are the optical efficiency and stability of the module under thermal and optical stress. For an automotive application, the module must work reliably in the temperature range of -40°C up to $+125^{\circ}\text{C}$. At the same time, it must be able to withstand illuminances of $\geq 20 \text{ Mlx}$ provided by the LED-matrix background lighting for several hours per use for the life span of a vehicle, which is considered to be ~ 15 years or 300,000 kilometers. To adhere to the regulations, a high beam should provide an illuminance of $>120 \text{ lx}$ on a surface 25 meters in front of the vehicle when turned on. When turned off, oncoming traffic at the same distance should not be exposed to more than 1 lx (based on both headlamps) to avoid glare. To fulfill these boundary conditions, a headlamp needs a contrast ratio $>240:1$. In order to ensure this ratio, the contrast of an AMLCD integrated in a headlamp should be considerably higher than that.

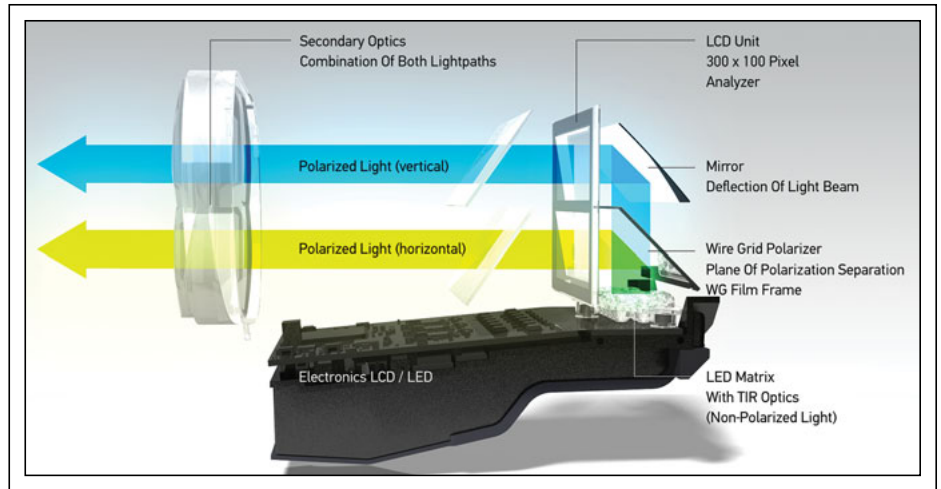


Fig. 3: The AMLCD high-beam design incorporates two discrete optical paths, one for each plane of polarization. Source: HELLA GmbH & Co. KGaA.

For an optimal contrast ratio, a twisted-nematic (TN) cell with perpendicular polarizers is a good possibility. Active-matrix TN-LCDs are a robust technology and easily adapted for headlamp applications. The limited viewing angle of a TN-cell is uncritical in this context, as the AMLCD is used for projection instead of displaying information. However, the thermal stability of standard liquid-crystal compositions used in flat screens does not encompass a nematic phase spanning at least 165°C between crystallization temperature and clearing point. Therefore, Merck KGaA developed a novel liquid-crystal composition specifically for this application.¹

The choice of a suitable thin-film transistor technology for the AMLCD backplane is

driven by the need for a reliable, cost efficient, and easily available technology. Amorphous silicon transistors (a-Si TFTs) are the most mature technology for AMLCDs and available at low cost. Considering their sensitivity to illumination, a-Si TFTs did not at first seem to be suitable for an application in headlamps. Typical input characteristics of a-Si TFTs under different lighting conditions are shown in Fig. 2(a). When the channel area is exposed directly to $>20 \text{ Mlx}$ illuminance, the input characteristics are severely impaired compared to measurements done under ambient light. However, as shown in,¹ a metallic light shield was applied, which improved the input characteristics sufficiently, even under 40 Mlx illuminance, to make a-Si TFTs

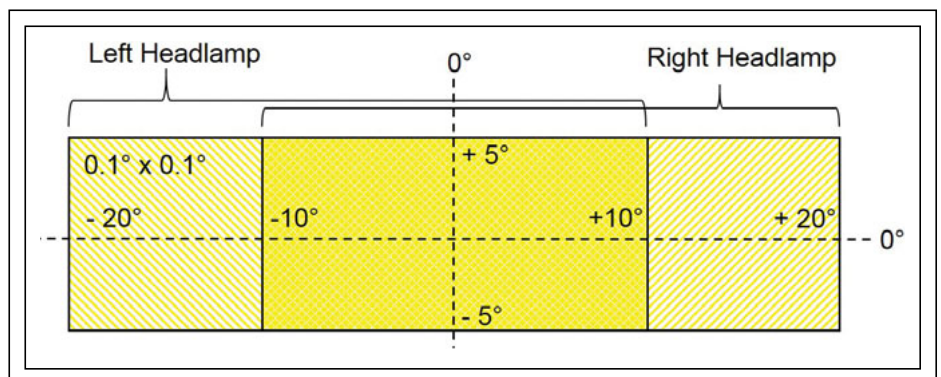


Fig. 4: Field of view – Each headlamp illuminates an area of 30° width and 10° height in front of the vehicle, overlapping in the central area. The 30K switchable pixels per headlight result in a resolution of $0.1^{\circ} \times 0.1^{\circ}$. Source: HELLA GmbH & Co. KGaA.

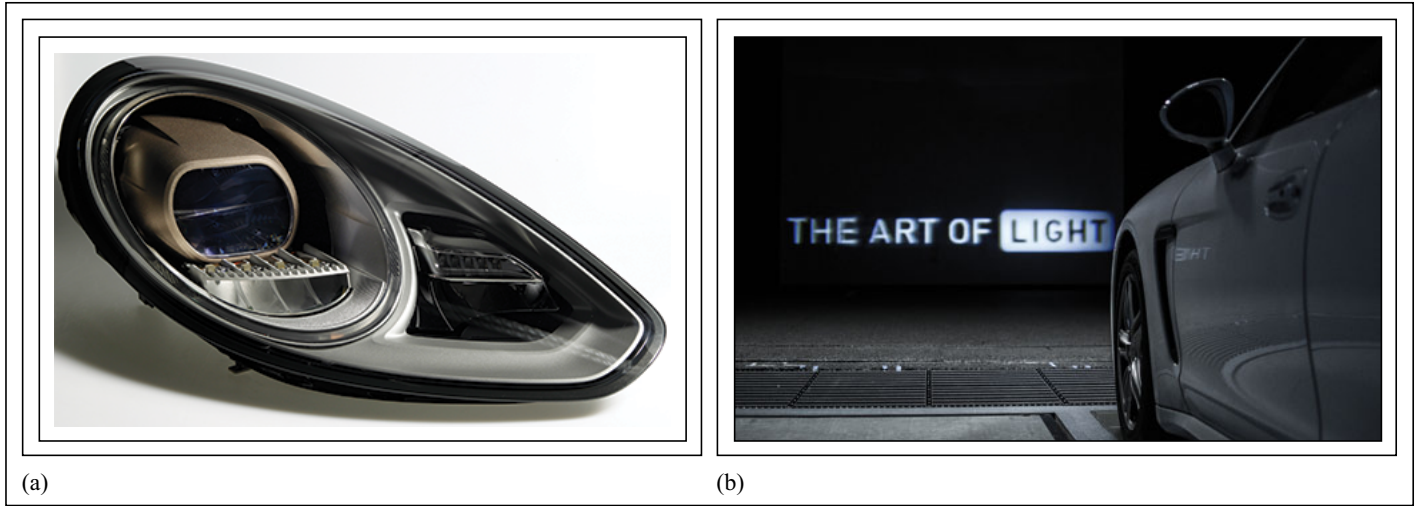


Fig. 5: At left (a), the AMLCD high beam with LED-matrix background lighting has been incorporated into a Porsche Panamera headlamp. At right (b), that headlamp's projection at a 10-meter distance is shown. Source: HELLA GmbH & Co. KGaA.

applicable in a headlamp module. Such a TN AMLCD with a-Si TFT backplane can be seen in Fig. 2(b).

In a typical AMLCD embodiment, at least 50 percent of the background lighting is lost in the first polarizer. This loss has to be decreased substantially to make an AMLCD-LED headlamp system that can compete with existing solutions. But in this case, the source of the problem is also the key to its solution. Standard display polarizer foils do not provide sufficient robustness against light and temperature stress to be usable in this application.

Therefore, the AMLCD module uses metallic wire grid polarizers instead. The solution to decreasing the losses implemented for the VoLiFa2020 headlamp¹ takes advantage of the properties of those wire grid polarizers to separate the background lighting into its two planes of polarization. Each polarization is then directed through its own active-matrix area. This results in two discrete optical paths, one for each plane of polarization (see Fig. 3). By this means, the optical yield of the generated light after the analyzer increases up to 80 percent. The two optical paths are then

recombined by secondary optics to create a homogeneous projection on the street 25 meters in front of the vehicle. This approach has the additional advantage of redundancy, allowing the system to compensate for pixel failures in one AM area with the information provided by the other.

The thermal management of the 25 LEDs, ECU, and optical components like the LCD and polarizers is done by an active cooling system. The system design is based on computational fluid dynamics simulations and includes a radial fan and air-guiding elements.

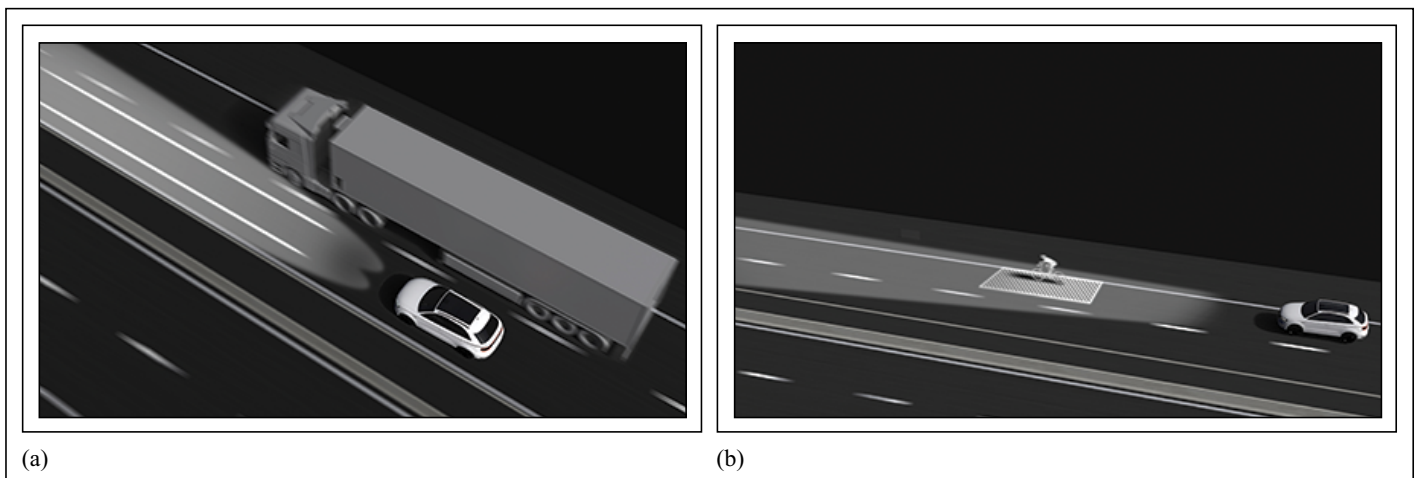


Fig. 6: Possible functionalities of adaptive headlights include indicating passing lanes (a) and bicycle safety zones (b). Source: HELLA GmbH & Co. KGaA.

The major obstacle was to balance the system regarding package space, thermal management, optical performance, power consumption, efficiency, styling, resolution, functionality, and field of view (Fig. 4).

By using polarizers, separating the planes of polarization, and choosing a suitable back-plane technology and a dedicated twisted-nematic (TN) liquid-crystal composition, an AMLCD high beam with LED backlighting can be made readily capable of providing ≥ 30 K switchable pixels per headlight to create fully adaptive lighting. The contrast ratio of the system implemented in the VoLiFa2020 headlamp was measured at up to 490:1, surpassing the minimum requirement of 240:1 considerably. The results were presented at Display Week 2017 in Los Angeles, earning a student paper award and the I-Zone Best Prototype Award. The VoLiFa2020 headlamp has been integrated in the headlamps of a Porsche Panamera test vehicle (Fig. 5), and perception studies are currently being conducted to evaluate and adjust new functionalities as a part of the project VoLiFa2020.¹

At the moment, the number of pixels that could easily be realized with an AMLCD surpasses the number of pixels that can be fed with real-time data computed from the input of the vehicle's sensors. This certainly will change in the future. However, the benefit of an increasing number of pixels and higher resolution reaches its limit at the threshold of human perception. The size and distortion of the projection of a single pixel as well as the unevenness of the projection area influence this perception. Further studies will show at which point the limit of added value per added pixel is reached.

Adaptive Headway

The new generation of headlamp systems creates non-analog light to provide fully adaptable lighting to increase the safety and comfort of the driver. Lighting functions like de-glaring other traffic and road signs, projecting distance warnings and navigation onto the street, and indicating safety zones for other road users as well as the width needed to pass other traffic safely (see Fig. 6) – to name some of the more prominent ones – can be realized simultaneously and in real time. Adding even more flexibility, specific light distributions for different requirements can be implemented without changing ray optics.

Lighting functions can be simply added, modified, or disabled by a simple software update to adapt to the lighting scheme of specific car brands, consumer preferences, regional conditions, or changing legislation.

Considering this, it is no wonder that the market share of fully adaptive headlamps has been rising steadily. Different approaches to creating a high-resolution headlamp that can adapt illumination with the least possible delay to ever-changing situations on the road are currently being investigated. An AMLCD module with LED-matrix background lighting is a state-of-the-art solution aimed at meeting these challenges.

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Curved Displays Challenge Display Metrology

Non-planar displays require a close look at the components involved in taking their measurements.

by Michael E. Becker, Jürgen Neumeier, and Martin Wolf

DISPLAY metrology — measurement and evaluation of the electro-optical properties of display devices — is crucial in order to obtain objective characteristics that specify the performance of such displays as a basis for purchasing decisions. The usability of displays for a certain application can be estimated on the basis of performance features obtained from standardized display measurements (see, for example, ISO-9241-3xx). In the R&D activities of companies that are manufacturing displays and products with displays, display metrology is necessary to obtain performance specifications for systematic product optimization.¹

Measurement and evaluation of the electro-optical performance of display devices are based on the target quantities **luminance** (corresponding to the visual perception of brightness) and **chromaticity** (corresponding to the visual perception of color). They comprise four main components:

- lateral variations,
- directional variations,
- variations vs. electrical input,
- temporal variations (long and short term).

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Evaluation of the recorded target quantities generally yields uniformities (or inversely, non-uniformities) and characteristic functions; that is, variations of the target quantity (electro-optical transfer function, or EOTF) from which characteristic values can be obtained (e.g., the exponent gamma from the EOTF).

Emissive displays — a fixed combination of transmissive LCD and backlight unit (BLU) can be considered as an emissive display — can be measured under darkroom conditions, but more realistic results are obtained when controlled ambient illumination is provided during the measurements. Reflective displays require external illumination sources to function. Realization of con-

trolled illumination is quite demanding and usually makes display metrology even more complex and delicate to handle.

A basic difficulty of electro-optical display metrology, not unlike metrology in other technical fields, is the reproducibility of the results — that is, the ability to obtain the same results across a range of laboratories, measurement setups, and operators. A necessary condition for reproducibility is the exact knowledge and specification of all measurement conditions, comprising the display under test (DUT), the light measurement devices (LMDs), their condition of application (*i.e.*, the measurement setup, including illumination devices), and the procedure.

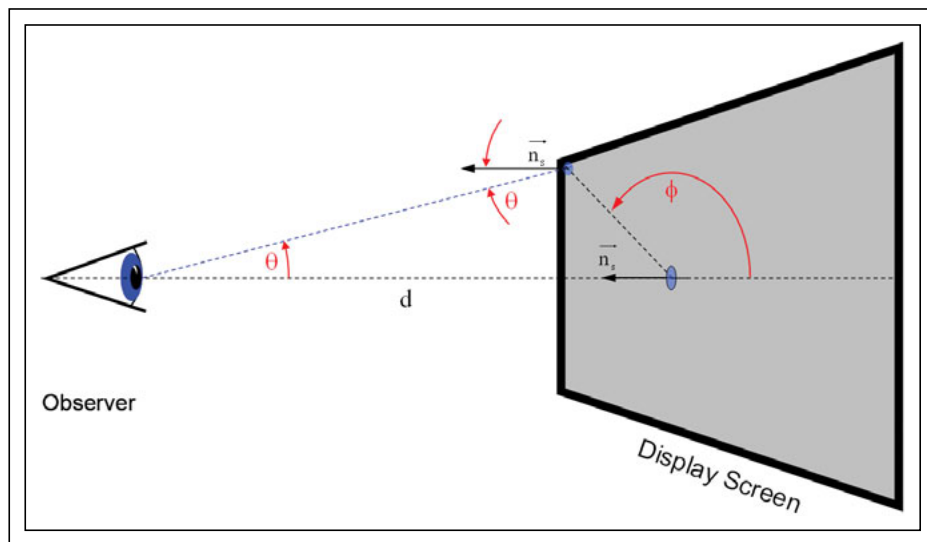


Fig. 1: The observer looks at every location on the display screen from a specific direction (viewing direction) specified by the spherical angles, θ (angle of inclination) and ϕ (azimuth).

This article describes the effect of the measurement field diameter and the LMD aperture on the directions included in one measurement for both spot LMDs and imaging LMDs for displays in general, and it points out the effect of the local display curvature. It identifies the critical aspects, evaluates the maximum angle of inclination quantitatively, and proposes precautions for routine measurements in the optical laboratory to yield reproducible and significant results.

Curved Displays

Curved displays were introduced to the TV segment of the display market some years ago with the objective of providing the user (observer) with a more “immersive viewing experience.” For TV and computer-monitor applications, the curvature is typically concave.

In the automotive-instrumentation sector, curved-form factors have been introduced to obtain a more seamless fitting of displays into the dashboard assembly — that is, the curvature is a design feature rather than an improvement on customer experience. In the automotive world, quality control is highly important in order to assure compatibility throughout the complete supply chain. This also requires unambiguous, well-specified, and standardized test and measurement procedures as a basis for reproducibility.

Convex-shaped displays are also encountered as wearable displays, especially when designed and worn as wristbands.

Variation of Perspective

When we observe a display screen, as sketched in Fig. 1, we look at each location on the screen from a specific direction (*i.e.*, viewing direction). This direction is specified by two spherical angles, the angle of inclination, θ (with respect to the display surface normal, n_s), and the azimuth, ϕ , with respect to a reference direction within the screen surface area (here: 3 o'clock direction) as indicated in Fig. 1. The viewing direction can be calculated from the viewing distance, d , and the coordinates of the location the observer is looking at. The corners of an office desktop monitor with 23-in. screen diagonal and a 16:9 aspect ratio are seen at an angle of inclination of 20° when the observer is 800 mm away from the screen center. Since the variation of luminance is usually continuous and gradual from the center to the corners, this

variation is not readily visible to the human observer; however, it may have a pronounced effect on optical measurements.

Typical Objects of Measurement

The optical properties of display devices (luminance and chromaticity) generally are a function of the direction of observation (viewing direction), not only in the case of LCDs but — in contrast to conventional wisdom and rather unexpected also for experts — also in the case of OLED displays.

Figures 2 and 3 illustrate the variation of luminance and chromaticity ($\Delta u'v'$) of a typical active-matrix-addressed OLED display (Fig. 2) and of a typical high-quality LCD screen (Fig. 3) with viewing direction in polar coordinate systems where every point corresponds to one viewing direction specified by angle of inclination, θ , and azimuth, ϕ , in the

upper row. The variation with angle of inclination, θ , with the azimuth as parameter is shown in the lower rows. These results are typical for current state-of-the-art display screens used in high-quality portable devices like smartphones.

The luminance decreases with angle of inclination; in the case of the OLED display, it decreases in a rotationally symmetric way. While the variation of chromaticity difference $\Delta u'v'$ (related to the normal direction) is larger for the OLED display, the luminance drop with angle of inclination is more pronounced for the liquid-crystal (LC)-display. Both variations are more rotationally symmetric in the case of the OLED display.

The corner locations of a computer monitor (23-in. screen diagonal and viewing conditions as introduced above) with a perfect lateral uniformity of luminance, would be

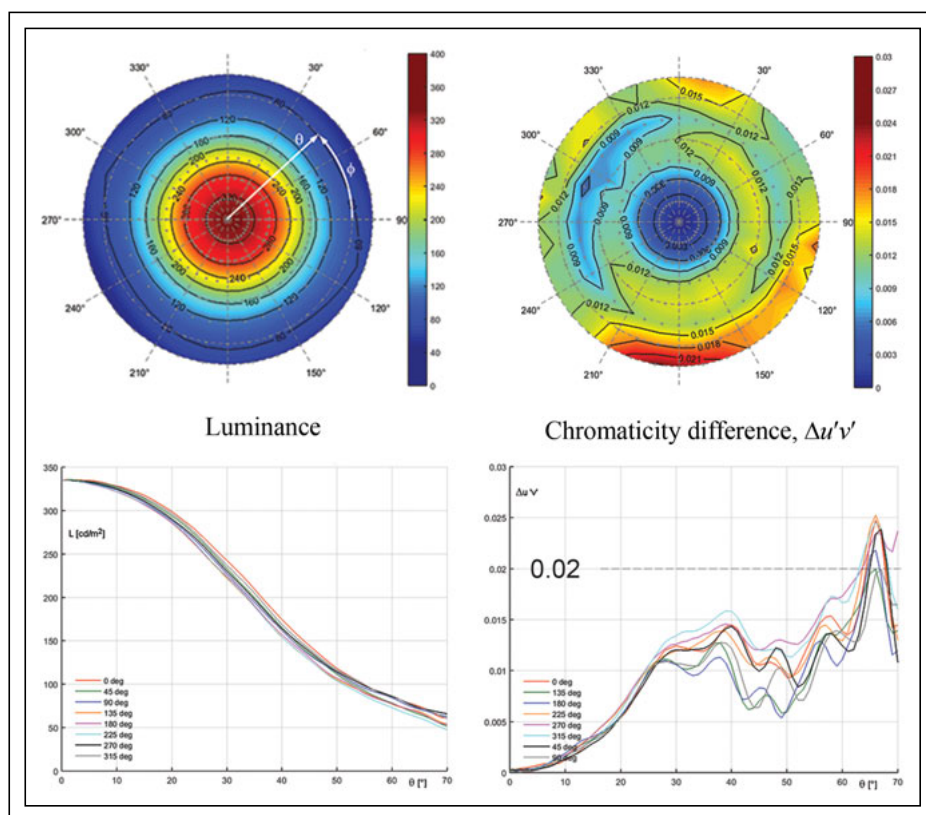


Fig. 2: Above is shown the variation of luminance (L) and chromaticity ($\Delta u'v'$) with viewing direction (θ , ϕ) for the white state of an active-matrix-addressed OLED display. Variations are shown by pseudo-color representations in polar coordinate systems (top row) and variation with angle of inclination, θ , with the azimuth as parameter (bottom row). The luminance decreases about 4 percent (13 percent) at an angle of inclination of 10° (20°). Measurements were performed with the DMS-803.²

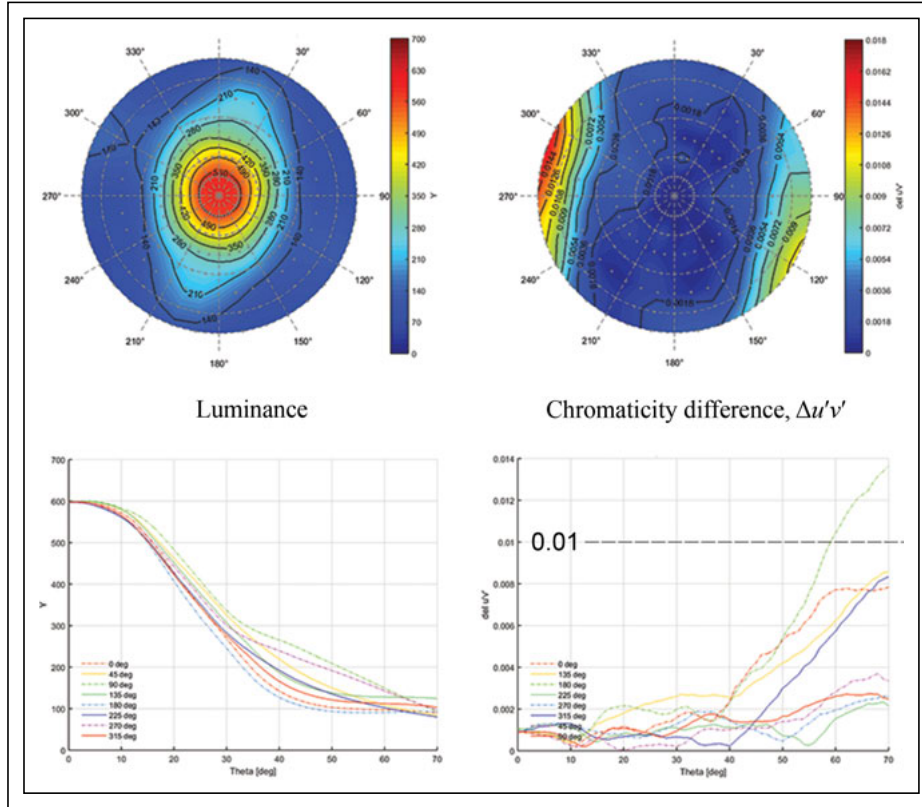
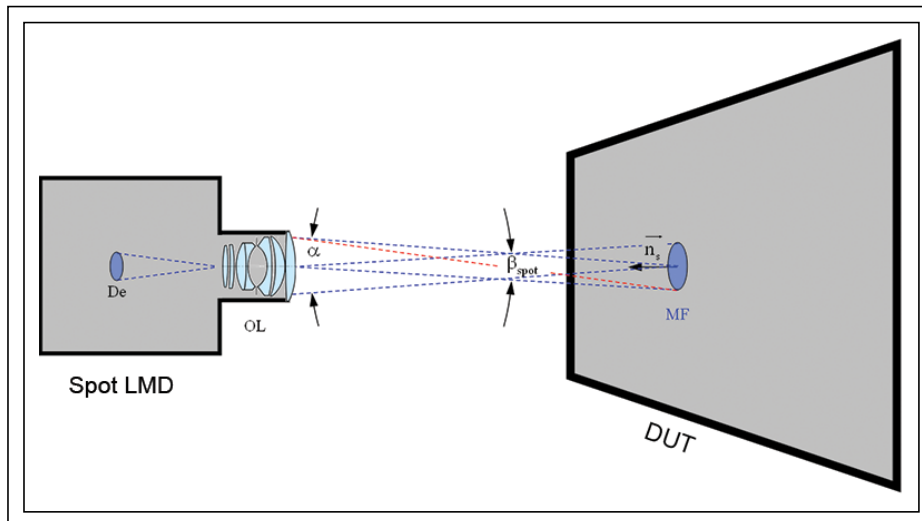


Fig. 3: Above is shown the variation of luminance (L) and chromaticity ($\Delta u'v'$), with viewing direction (θ, ϕ) for the white state of an active-matrix addressed LC-display screen. Variations are shown by pseudo-color representations in polar coordinate systems (top row) and variation with angle of inclination, θ , with the azimuth as parameter (bottom row). The luminance decreases about 4 percent (20 to 30 percent) at an inclination of 10° (20°). Measurements were performed with the DMS-803.²



seen as 13 percent (OLED display) or 19 to 32 percent (LC display) darker than the center location due to the decrease of luminance with angle of inclination as illustrated in Figs. 2 and 3, and summarized in Table 2.

Since no displays are currently available with perfectly uniform directional emission characteristics (*Lambertian*), care has to be taken during measurement to assure that lateral and directional variations are not mixed up, thus affecting the results in a nontrivial, unintended, and nonreproducible way. While this is also true for the measurement of planar displays, it becomes more critical in the case of convex curved displays. It is most important when imaging light measurement devices (iLMDs) are used for “convenient” evaluation of lateral variations of luminance and chromaticity, because the large-measurement-field angles cause a mixing of lateral and directional properties of the display that cannot be separated later on.

Light-Measurement Devices

Depending on the kind of opto-electronic detector used, we can distinguish two classes of light-measurement devices: spot LMDs (LMDs), performing an integration over the measurement field (*i.e.*, measurement spot) and thus delivering one measurement value (for example, luminance), as shown in Fig. 4, and imaging LMDs (iLMDs) with an array of detector elements providing an array of measurement values (see Fig. 6).

As illustrated in Fig. 4, the aperture of the LMD objective lens performs a directional integration over the solid angle α while the detector element performs a lateral integration over the field of measurement. The red ray in Fig. 4 extending from the periphery of the measurement field to the opposite periphery of the lens aperture is the ray with the maximum inclination with respect to the optical axis of the LMD, which is parallel to the surface normal of the DUT, \vec{n}_1 .

Fig. 4: This schematic shows a spot LMD with opto-electronic detector element (De), objective lens (OL), and a display under test (DUT). The measurement field angle, β_{spot} , usually is 1° or smaller; the aperture angle, α , is given by the clear aperture of the objective lens and the distance to the circular measurement field, MF, on the DUT.

For evaluation of directional variations, the aperture angle should not exceed 5°, according to IEC 61747-6-2. In typical LMD realizations, the measurement field angle is 1° or smaller (often selectable), and the aperture area of the objective lens is fixed. The distance between the LMD and the DUT determines the actual size of the measurement field on the DUT as well as the aperture angle.

With the quantities illustrated in Fig. 5, the angle of inclination (θ_i) at the periphery of the measurement field (MF) with respect to the local surface normal (\vec{n}) is obtained as:³

$$\theta_i = \arcsin \left(\sin \left(\arctan \left[\frac{d_A + d_{MF}}{2d_w} \right] \right) \cdot \left[1 + \frac{d_w}{r} - \frac{d_A \cdot d_w}{(d_A \cdot d_{MF}) \cdot r} \right] \right) \quad (1)$$

with

- d_A diameter of the objective lens aperture
- d_w distance between the lens and the measurement field
- d_{MF} diameter of the measurement field
- r radius of the cylindrical DUT

Equation (1) can be used to evaluate the effect of the involved parameters on the range of inclinations over which the LMD integrates ($-\theta_i$ to $+\theta_i$). For planar samples, $r \rightarrow \infty$ and thus

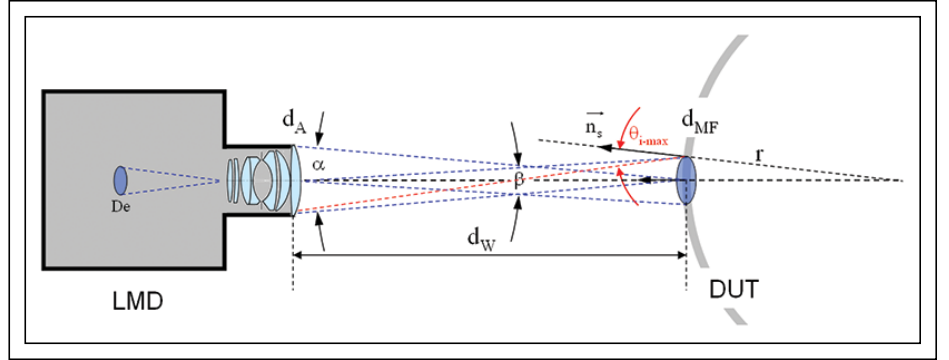


Fig. 5: The angle of inclination (θ_i) at the periphery of the measurement field (MF) with respect to the local surface normal (\vec{n}) is given by the diameter of the objective lens aperture (d_A), the distance between the lens and the measurement field (d_w), the diameter of the measurement field (d_{MF}), and the radius of the cylindrical DUT, r .

$$\theta_i = \arcsin \left(\sin \left(\arctan \left[\frac{d_A + d_{MF}}{2d_w} \right] \right) \right) \quad (2)$$

During measurements of cylindrical DUTs with spot LMDs, the diameter of the measurement field should generally be kept as small as possible under consideration of the signal-to-noise ratio of the measurement.

Since the measurement field angle of the LMD is constant by principle (see Fig. 4), the measurement field diameter increases with working distance while the aperture angle, α ,

continuously decreases. As a result, the angle of inclination at the periphery of the measurement field, θ_{i-max} , exhibits a minimum when the aperture diameter is not zero. This is the preferred working distance, d_{wp} , indicated by the yellow cell background in Table 1.

Measurement of Lateral Variations

Lateral variations of luminance and chromaticity are often measured with imaging LMDs because the complete DUT can be captured in “one shot” and no time-expensive

Table 1: Below is shown the angle of inclination at the periphery of the measurement field, θ_{i-max} , as a function of the measurement field angle, β , the aperture diameter, d_a , the cylinder radius, R_{cyl} , and the working distance, d_w according to Eq. (1). At the preferred working distance, d_{wp} (yellow cells), θ_{i-max} has a minimum. The preferred working distance is indicated by the yellow cell background.

Beta [°]	1																	θ_{i-max} [°]
da [mm]	10																	
	R _{cyl} [mm]	10	20	30	40	50	60	70	80	90	100	200	300	400	500	1000	planar	
dw [mm]	d _{MF} [mm]																	
50	0.87	8.71	7.46	7.04	6.83	6.71	6.62	6.56	6.52	6.48	6.46	6.33	6.29	6.27	6.26	6.23	6.21	
60	1.05	8.27	6.76	6.26	6.01	5.86	5.76	5.69	5.63	5.59	5.56	5.41	5.36	5.33	5.32	5.29	5.26	
70	1.22	8.09	6.34	5.75	5.46	5.28	5.17	5.08	5.02	4.97	4.93	4.76	4.70	4.67	4.65	4.62	4.58	
80	1.40	8.09	6.08	5.41	5.07	4.87	4.74	4.65	4.57	4.52	4.47	4.27	4.21	4.17	4.15	4.11	4.07	
90	1.57	8.19	5.93	5.18	4.80	4.58	4.43	4.32	4.24	4.18	4.13	3.90	3.83	3.79	3.77	3.72	3.68	
100	1.75	8.38	5.87	5.03	4.61	4.36	4.19	4.08	3.99	3.92	3.86	3.61	3.53	3.49	3.46	3.41	3.36	
200	3.49	12.01	6.95	5.27	4.43	3.93	3.60	3.36	3.18	3.04	2.93	2.43	2.27	2.18	2.13	2.03	1.93	
300	5.24	16.68	8.99	6.47	5.21	4.46	3.96	3.60	3.33	3.12	2.96	2.20	1.95	1.83	1.75	1.60	1.45	
345	6.02	18.92	10.00	7.10	5.65	4.78	4.21	3.80	3.49	3.25	3.06	2.19	1.91	1.76	1.68	1.50	1.33	
500	8.73	27.06	13.70	9.45	7.34	6.08	5.25	4.65	4.20	3.85	3.57	2.32	1.91	1.70	1.57	1.32	1.07	
1000	17.45	62.42	26.75	17.73	13.41	10.85	9.16	7.95	7.05	6.35	5.80	3.29	2.45	2.04	1.79	1.29	0.79	

mechanical lateral scanning (as would be the case with spot LMDs) is required. The geometry of such a setup is the same as the one shown for the observer in Fig. 1.

Measurement-field angles of spot LMDs, β , are typically in the range of 1° (and below),

while that angle may increase to 40° (with wide-angle lenses; typically 20° and below) in the case of imaging LMDs. When such instruments are applied to the evaluation of lateral variations of luminance and chromaticity, directional effects may become pronounced at

the periphery of the field of measurement even in the case of planar DUTs (see Fig. 1). In the case of convex cylindrical samples, the angle θ_i (angle of inclination) varies even more across the field of measurement, as illustrated in Fig. 6. In the case of concave cylindrical DUTs only, this variation is reduced when the LMD is located on the cylinder axis.

When the directional variations of the DUTs are known (see Figs. 2 and 3 and Table 2), we can determine the minimum working distance that corresponds to a maximum permitted angle of inclination and thus to the amount of luminance variation caused by directional variations; but not, however, by lateral variations.

If the percentage of directional effects on the lateral variation of luminance is supposed to stay below 1 percent for the OLED display and 2 percent for the LC display (see Table 1), the distance between LMD and DUT has to be adjusted according to the values obtained from Eq. (1) (cylindrical DUT) and Eq. (2) (planar DUT).

In order to make such measurements reproducible, the parameters according to Table 3 have to be evaluated and specified.

When concave cylindrical DUTs are measured, the variation of the local angle of inclination is generally reduced. With the LMD positioned in the center of the concave cylinder, every location on the DUT within the vertical plane containing the optical axis is measured from the normal direction, which means that for this special geometrical condition, there is no variation of θ_i at all.

Imaging LMDs have been calibrated by the manufacturer of the instrument in such a way that the luminance (radiance) of a uniform planar light source produces a uniform array of output values. During that calibration, the LMD is focused on the plane of the light source. It also must be ascertained during calibration that the aperture of the LMD is overfilled by the light entering from each DUT area element. Deviations from those conditions may result in measurement errors (for example, focusing errors). The effect of defocusing during the measurement of cylindrical samples has been analyzed in detail by Yu *et al.*⁴ They concluded that the measurement uncertainty is dominated by the characteristics of the cylindrical DUT, namely the directional characteristic of emission and the cylinder radius. Uncertainties increase with

(continued on page 28)

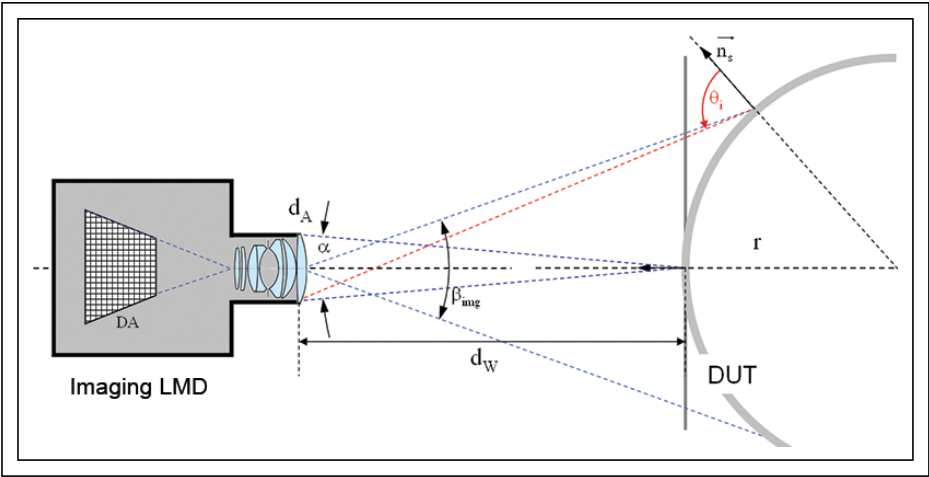


Fig. 6: Here, an imaging LMD is applied for the evaluation of, e.g., the luminance of a cylindrical DUT. With the measurement field angle, β_{img} , up to 40° (typical 20°), the variation of the angle of inclination across the DUT is more pronounced and thus affects the results. In addition, the area element at the periphery of the measurement field is more distant from the lens than the on-axis area element and thus defocusing takes place.

Table 2: The decrease of luminance with angle of inclination relative to the normal direction from the results shown in Fig. 2 and Fig. 3.

DUT	Inclination	5°	10°	20°	30°
OLED Display		1%	4%	13%	28%–35%
LC Display		2%	5%	19%–32%	43%–58%

Table 3: The above items and parameters should be specified for DUT, LMD, and setup.

DUT	Specifications	
	LMT	Setup
Test pattern	Aperture area	MF diameter and location
Temperature	MF angle	Measurement distance
Location of cylinder axis, radius of cylinder	Data acquisition timing	Intersection of optical axis
Software settings, e.g., rendering intent		Measurement direction

Q&A with Visionect

Visionect is a 10-year-old company based in Ljubljana, Slovenia, that develops ultra-low-power digital signage. ID magazine recently talked with Visionect CEO and founder Matej Zalar and Visionect board member Sri Peruvemba about the company's products and plans, as well as its lessons learned.

Information Display:

What's the history of Visionect? How did the company get started?

Matej Zalar:

Our three founders [Rok Zalar and Luka Birsa, in addition to Matej Zalar] started working together about 10 years ago. From the beginning, we were working with electronic paper, trying to build some kind of low-power device with it. I had been studying economics in Finland, where I was also doing some projects for Nokia. I discovered electronic paper at Nokia, and I thought it looked exciting.

Our first electronic-paper-based product was issued in 2010. It was called Geoffrey, and it was a tabletop ordering menu for restaurants. It was waterproof, and at the time you didn't have many waterproof devices. It was also visible in direct sunlight, so it worked well in beer gardens and outdoor restaurants.

ID: What were some of your biggest challenges with regard to getting that first product to market?

MZ: As a new company, the challenges are always cash and time. Creating the physical device is definitely easier and faster now.

Matej Zalar is the founder and CEO of Visionect, a world leader in deploying digital signs in challenging environments. The result of a decade of market-leading expertise, Visionect technology excels in versatility, ultra-low power consumption, ease of installation, and simplicity of use. Visionect is the maker of JOAN room-scheduling technology and the Place & Play signage concept.

Sri Peruvemba is a member of the board at Visionect. His two decades of experience in the display industry include a decade of management roles at e-paper companies.

This article is based on phone and email interviews conducted by Jenny Donelan, editor in chief of Information Display.

Ten years ago, we didn't have rapid prototyping technology, or 3D printers, so developing new products was much more time and resource consuming. Also, when we made a mistake it took much more time correcting it. In those days we used traditional ways of launching a product – we made it based on our best assumptions of customer needs, then tried to

reach as many customers as possible. We did not always get early customer feedback like we do now. I do think that everything that did not work was a very valuable learning experience for us. Today we can be much faster also because we know better what not to do, and what does not work.

ID: After Geoffrey, Visionect introduced some additional e-paper based products – JOAN and the newest one, Place & Play. Can you tell us about these and what the differences are between them?

Sri Peruvemba:

JOAN is a 6-in. or 13-in. diagonal, wireless, low-power display, which is basically used as a conference room sign. There are different products in the portfolio, including JOAN Board, which is used for monitoring multiple meeting rooms, and also single JOAN units. You could use Place & Play, which is 13.3 inches diagonal, for a conference room sign, but in general it will be used more as a monitoring station or for other applications. You can also display it in an industrial/medical environment like a factory floor or hospital room or someplace where you don't want the distraction of an LCD – an LCD looks like a TV that is constantly updating and shining light into your eyes, but Place & Play looks like paper. And it is extremely low power. You can use this product in a location where it's not possible to have a power cable. It will even stick to a glass wall, and it goes a whole year without a recharge.

ID: When will Place & Play be commercially available?

SP: It's shipping now. With the rollout of Place & Play, Visionect did something really clever. They started by speaking to a lot of customers about their needs and then they created the product and did a beta test with about 30 or 40 customers. That was several months ago, and now they're shipping Place & Play to customers worldwide.

MZ: We started our adoptive customer program with JOAN, which is our most successful product to date. About 2,500 companies are using multiple JOAN products. Now we repeat this program with every new product. If we were developing Geoffrey now, we would definitely start out with the early adoption program. With Geoffrey [which is no longer sold], we learned, for exam-



Matej Zalar

ple, that the hotel and restaurant industry is quite complex. You have to have very strong relationships with the cash register companies, and you need tight integration with their software. When we launched Geoffrey, we knew how to build the display but we didn't know very much about the hotel and restaurant business.

ID: Back to your beginnings – You've been working with E Ink and other partners for quite a few years. Do you think you have informed their product evolution as your own products have been developed?

SP: Visionect is probably one of the oldest customers of E Ink. [Note: Peruvemba was formerly chief marketing officer for E Ink.] In 2007, when Visionect launched, there was no Kindle [which first sold in November 2007]. There weren't any widely available software tools. E Ink itself was not yet mainstream. In 2007 E Ink was a startup with a small team, and Visionect had just started. I'm sure both of these companies contributed to each other at one time or another. Collaboration is definitely two way, and it's very healthy and has grown stronger over the years. E Ink continues to be very supportive of Visionect today.

ID: What challenges are you facing as the company grows?

MZ: In the past 10 years, Visionect has grown from a company of three students to close to 40 people. You have to grow up, and move from "everybody does everything" mode to a more professionalized structure.

Also, when you are venture funded, you have to learn how to grow quickly. Finding a VC [venture capitalist] always takes time. In many cases it takes from 6 to 12 months of intense relationship building. Investments don't happen overnight. VC investments are like marriages. You have to build trust and relationships, and you cannot build that over one face-to-face meeting. After the investment, you have to be able to move fast, grow fast, and expand fast. It takes a different mentality and



Sri Peruvemba

strategy (especially for EU companies) when you decide to go the VC-funded way.

ID: What's the role of marketing in your success?

SP: Even Fortune 500 companies would be envious at how well Visionect does its marketing. Their images are really great looking. Their brochures are awesome – and none of it is out-sourced. It's all done in house. They're very creative. They have a strong outbound marketing program, and are very customer focused.

ID: Do you manufacture in-house, in Slovenia?

MZ: We assemble in Slovenia, using parts from Germany, China, etc. It all goes together like Legos!



Low-power e-paper signage at this bus stop in Ljubljana, Slovenia, is by Visionect. Ljubljana was named "European Green Capital" for 2016 by the European Commission. Photo by Sri Peruvemba.

business of displays

ID: What is the tech scene like in Slovenia?

MZ: It is growing, more and more. Traditionally, Slovenia has always had very good universities, but we were not very good at selling. We had zero history doing startups in this part of Europe. But that has changed in the past 10 to 15 years. We have many younger companies, and industry is growing.

You need role models. Basketball is an example. Last September, Slovenia won the European Basketball Championship, and since then, for the past two or three months, every other kid is playing basketball. Basketball schools are full.

ID: Sri, what's been your experience of working with Visionect?

SP: Visionect has that kind of energy that you only see in startups. They're enthusiastic, they're eager – they really do things. It's a joy working with these guys.

ID: How have sales been?

MZ: In general, we have been growing more than 100 percent year over year over the past four years.

ID: What are the company's plans for the future? What kinds of products are you working on?

MZ: Our mission is to help people make better decisions in public spaces by delivering more relevant information through our ultra-low-power display network. We plan to focus on building more end products like JOAN and supporting larger sizes of e-paper displays. We are also currently focusing on establishing a strong distribution network in the EU and North America with our local partners. ■

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making displays work for you

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increasing curvature (decreasing radius) and at the edges of the cylinder.⁴

Measurements Under Ambient Illumination

A further complication in measurement of non-planar displays is added when reflective displays are measured or when the performance of emissive displays has to be evaluated under ambient light illumination. In that case it must be ascertained that the illumination conditions (hemispherical diffuse or directional) are uniform over an area that is larger than the measurement field. Several papers concerning measurements of reflective displays under hemispherical diffuse illumination^{6,7,8} and the reflective properties of cylindrical emissive displays have been made available through various publications of the SID.⁸

Curved Displays Demand Careful Measurements

Even though non-planar displays do not necessitate the creation of a new chapter of display metrology, they provide strong reasons for a closer look at the components involved in such measurements and the conditions of their application (*i.e.*, measurement setup) in order to specify the relevant parameters completely and in detail, as a basis for reproducible measurement results.

The higher the local curvature of convex cylindrical displays is in the case of spot LMDs, the smaller the field of measurement should be. When directional variations are being evaluated, the increase of the measurement field with angle of inclination has to be considered.

The imaging conditions of imaging LMDs have to be controlled to avoid unintended and uncontrolled mixing of directional and lateral variations of luminance, contrast, and chromaticity, and they have to be specified in detail to make measurements reproducible. The effect of defocus and the related low-pass filtering (blurring) have to be considered when small details (*i.e.*, high-frequency components) have to be identified by imaging LMDs.

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I-Zone

Display Week 2018

Innovation Zone (I-Zone)

May 22–24, 2018

The prototypes on display in the Innovation Zone at Display Week 2018 will be among the most exciting things you see at this year's show. These exhibits will be chosen by the Society for Information Display's I-Zone Committee for their novelty, quality, and potential to enhance and even transform the display industry. These products will not only fire your imagination, but provide an advance look at many of the commercial products you'll be using a few years from now.

Apply to be part of the I-Zone at:

www.sid.org/About/Awards/I-Zone.aspx

Information DISPLAY

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2018 EDITORIAL CALENDAR

■ March/April

Display Week Preview, Emissive Technology

Special Features: SID Honors and Awards; Symposium Preview; Display Week at a Glance; Commercialization of Quantum-Dot Light-Emitting Diodes; MicroLED Displays; New Processes for High-Resolution MicroLED Displays; OLED Manufacturing

Markets: OEMs, deposition equipment manufacturers, panel fabricators, materials industry research and developers, display and electronic industry analysts, OLED process and materials manufacturers

February 28: Ad closing

■ May/June

Display Week Special, Wearables

Special Features: Display Industry Awards; Products on Display; Stretchable AMOLEDs; Stretchable TFTs; Cutting-Edge Applications for Wearables; Sensors; Smart Fabrics

Markets: OEMs, deposition equipment manufacturers, panel fabricators, materials industry research and developers, display and electronic industry analysts, wearable designers

April 18: Ad closing

Bonus Distribution: Display Week 2018 in Los Angeles

■ July/August

Display Week Review Special Part 1, AR/VR

Special Features: Display Week Highlights from the Show Floor; Materials Advances at Display Week; Best in Show and I-Zone Winners; AR/VR Advances; Light-Field Breakthroughs

Markets: Research institutions, OEMs, entertainment industry research and development, consumer product developers, display industry research and developers, display industry analysts

June 18: Ad closing



■ September/October

Display Week Review Special Part 2

Special Features: Display Week Technology Reviews: High-Definition Displays, Automotive Displays, Metrology, Imaging, and Digital Signage

Markets: Large-area digital signage developers; OEMs; consumer product developers; display industry research and developers; display industry analysts; metrology manufacturers; automotive and automotive display manufacturers; entertainment industry manufacturers

August 22: Ad closing

■ November/December

Stretchable/Flexible Technology

Special Features: Advances in Stretchable AMOLEDs; Stretchable Oxide TFTs and LEDs; Challenges in Manufacturing Stretchable Substrates and Electronics; From Flexible to Foldable

Markets: OEMs, consumer product developers, research institutes, entertainment and gaming developers, panel fabricators

October 18: Ad closing



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Jim Chen: In Memoriam



Dr. Hsing-Yao "Jim" Chen

Long-time SID member Dr. Hsing-Yao "Jim" Chen passed away on Wednesday, November 1, 2017, in Barrington, Illinois. He was 86 years old.

Chen was born in Fuzhou, China, to the late Dr. K.C. and Tan Chen. He obtained a Ph.D. in electrical engineering from the University of Connecticut in 1968. During his career, he worked at CBS Labs on a NASA project; at Zenith on flat-panel displays; and at RCA, where he became an expert in electron gun design and received the prestigious David Sarnoff Award. For the last 20

years of his career, he worked for CPT (in Taiwan). He was granted more than 50 patents, primarily pertaining to CRT electron guns, and served as an adjunct university professor in China.

Chen was active in the Society for Information Display for many years, helping to establish chapters in Taipei and Beijing. He was the founding director of the Taipei chapter, serving in that capacity from 1991 to 1993. He was an SID Fellow and lifetime member of both SID and IEEE (Institute of Electrical and Electronics Engineers), and served on SID's Honors and Awards Committee from 2002 to 2012, and on SID's Symposium Program Committee from 1989 until his death in 2017. "Jim believed SID was an important asset to the display community," says his wife, Sylvia Chen. She adds that he enjoyed working with young engineers and helping them to advance in their fields.

After retiring at 80, Chen remained active with SID and also worked on "passion projects" involving fusion and global warming. He loved traveling the world and spending time with his family and friends.

Jim is survived by Sylvia, his wife of 52 years; daughter Elizabeth Echternach of Lititz, Pennsylvania; son Steven Chen of Nashua, New Hampshire; daughter Deborah Chen-Sloan of Landisville, Pennsylvania; and four grandchildren: Drew Echternach, Erika Echternach, Ethan Chen, and Alex Chen. His two younger sisters, Shouhua Chen de Yearwood and Sue May Chen, live in Taiwan, and his three brothers (Xing-Guang Chen, Lawrence Hsing-Hsia Chen and Hsing-Chang Chen) predeceased him.

Donations in Dr. Chen's memory may be sent to either: FOMT (Friends of Mariners Trail), Box 2341, Manitowoc, WI 54221-2341; or to JourneyCare Foundation, 2050 Clair Court, Glenview, IL 60025 (www.journeycare.org).

Submit I-Zone Proposals Now

Since its launch six years ago, the Innovation Zone (I-Zone) has become one of the most popular aspects of Display Week. At the 2018 show, SID will once again host live demonstrations of cutting-edge information display and related technologies in the I-Zone. Since the number of I-Zone participants has doubled, from 22 in 2012 to more than 50 in 2017, The 2018 I-Zone will take place in two separate areas in the main exhibit hall (Fig. 1).

The I-Zone, which is sponsored by E Ink, provides space to startup companies and others to demonstrate their prototypes or other hardware demo units for three days free of charge on a dedicated area of the show floor at the premier display exhibition in North America.

The I-Zone committee encourages participation by small companies, startups, universities, government labs, and independent research labs. Proposals to demonstrate new displays, input technologies, and innovations in related fields such as lighting and organic electronics

will be considered. Technologies should be in the pre-product stage or at least have been on the market no earlier than January 2018. Demos that will be shown for the first time in a public forum at I-Zone are especially encouraged.

Submissions are due by March 9, 2018, and should include a 100-word abstract; a one-page summary describing the novelty and potential application; any relevant photographs, videos (no longer than 3 minutes), or diagrams; and a brief logistics plan for the intended demo. For complete instructions, be sure to review the information on the I-Zone web site (<http://www.sid.org/About/Awards/I-Zone.aspx>) and on the submissions form.

At the show, the I-Zone Committee will select a "Best I-Zone Prototype at Display Week 2018," to be announced on the show floor during Display Week and in the post-Display Week issue of *Information Display* magazine. Last year's winner was IGM University of Stuttgart and HELLA KGaA Hueck & Company's novel automotive headlamp that incorporates both active-matrix LCD and LED technologies. (See IGM's article about this technology in this issue.) ■

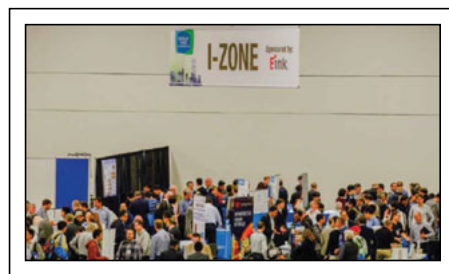


Fig. 1: The I-Zone is always one of the most popular areas of the exhibit hall.

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continued from page 2

The first article describes how the management of our circadian rhythms can be affected by our exposure to differing spectrums of light at different times of the day. Author Mariana G. Figueiro, director of the Lighting Research Center (LRC) and professor of architecture at Rensselaer Polytechnic Institute in Troy, New York, describes the LRC's latest work in the Frontline Technology article, "Biological Effects of Light: Can Self-Luminous Displays Play a Role?"

The second article in this set specifically addresses my desire for innovative lighting solutions that produce natural, diffuse, ambient light without glare and can be affordable for use in homes as well as commercial spaces. In her Display Marketplace article, "OLED Lighting Hits the Market," author Giana Phelan, director of business development at OLEDWorks, describes how the latest innovations in OLED technology are creating exciting new opportunities. Giana's survey not only describes the potential opportunities, but spells out the practical technical details associated with implementation of OLED luminaires. We've seen a lot of good notional ideas of how OLED lighting can be a great opportunity for designers and architects, but now, finally, I think we're crossing the chasm to practical commercial solutions for everyone. And, thank you again Marina for your great work in selecting these stories for us.

Revolutionary Headlamps

Another market area that is increasingly important to the display community is automotive. In so many ways, display and lighting technology are coming to define the most critical design elements of new cars. Much of that effort has been focused on the interior of the vehicle, where there is a need to convey information and manage the interior ambient experience. But another important element of car design is the performance of the lights on the outside, specifically the headlights. It's well understood that today's headlight designs are lacking in critical areas, including the characteristic of fixed beam patterns and limited modes for adjusting intensity. Some clever new (mostly mechanical) enhancements have recently been seen but none so clearly innovative as the concept we saw last summer in the Display Week 2017 Innovation Zone (I-Zone) from IGM, University of Stuttgart, in partnership with HELLA KGaA Hueck & Co. Their demonstration

featured a high-intensity light source, a low-resolution LCD panel, and some optics very reminiscent of projection optics from the LCOS days. The result was a high-resolution steerable beam headlight demonstration that won the I-Zone Best Prototype Award for 2017.

In their Frontline Technology article, "High Resolution LCD Headlamps for Intelligent Lighting," authors Christiane Reinert-Weiss and David Duhme describe the current state of the art, the dimensions of the problem they set out to solve, and the details of their paradigm-shifting innovation. Among the problems was the issue of losing the unselected polarization mode of the light through the LC panel. This would theoretically limit the luminous efficiency to below 50 percent.

Their clever solution passes both horizontal and vertical polarization modes through different areas of the same LC panel and then re-combines them. It's a relatively easy thing to do as long as you have much greater pixel resolution than you need. And though it sounds simple, this innovation is critical to achieving the necessary optical power efficiency at an affordable cost point for commercial adoption. The result is a smart-enabled solid-state headlight system that can be adjusted to any light level and beam pattern needed based on inputs from the onboard processing systems in the vehicle. I truly think this is a revolutionary achievement, and someday you can say you read about it here first.

Metrology and Business

Beyond lighting there are countless other areas of ongoing research and one of these is display metrology. Through International Committee for Display Metrology (ICDM) meetings at Display Week events and other standards-based activities, people are working hard to keep up with the new formats and technologies of displays that need accurate, appropriately engineered measurement methods. One such area with associated work is described in our Making Displays Work for You feature, "Curved Displays Challenge Display Metrology," written by colleagues Michael E. Becker, Jürgen Neumeier, and Martin Wolf from Instrument Systems GmbH, in Munich, Germany. In this very detailed study, the authors describe the issues that curved displays impose on existing measurement equipment and methods, making a compelling case for how those methods can

be adapted for best results. This is a significant body of work very well documented for further consideration, and we truly appreciate Michael, Jürgen, and Martin investing their considerable time to bring this article to us.

In our Business of Displays feature this month, Jenny Donelan details her interview with Matej Zalar, CEO and founder of Visionect, a startup company based in Ljubljana, Slovenia, that develops ultra-low-power digital signage. This conversation also included Sri Peruvemba, board member of Visionect and SID director of marketing. At Sri's invitation, Jenny and I also met with Visionect about two years ago at E Ink's headquarters in Massachusetts. Visionect was an early adopter of E Ink e-paper for its first product, "Geoffrey," which provided a tabletop menu application for restaurants. Since then, the company has started producing office automation products and experienced a lot of the classic challenges small companies go through to develop, market, and mass-produce their new products. I think you will enjoy this very candid and educational interview with Matej and Sri.

Unfortunately, we also have some sad news to share. We were dismayed to hear of the passing of Dr. Hsing-Yao "Jim" Chen in November 2017. Many of us knew Jim, and also his impressive roster of technical achievements. But more importantly, we knew him for his engaging and caring personality. Whenever he and I met each year at SID national events, Jim was always generous with his time – happy to answer questions and to offer suggestions on a number of matters. He was well respected by all for his engineering expertise and widely recognized for his substantial efforts to further the interests of SID. Our SID News article this month by Jenny Donelan has more details on Dr. Chen's life and legacy.

Before we end, let me offer a truly heartfelt wish for your good health, success, and prosperity in this New Year. We all have our individual hopes for 2018 and beyond. In recent years, I have been able to spend more time with my family and enjoy the things I truly cherish. I hope you too have similar ambitions. As I have written many times, a better work-life balance actually makes you more productive and more prosperous than endless working hours ever will. May we all find our own form of peace and happiness in the New Year. ■

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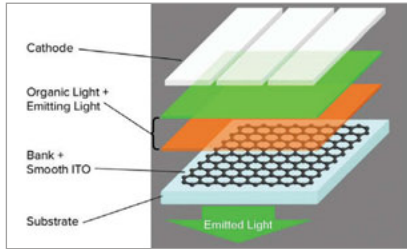
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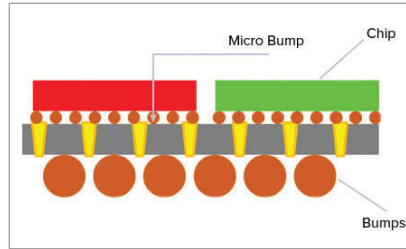
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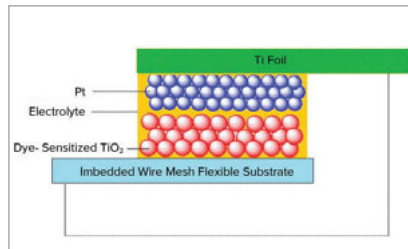
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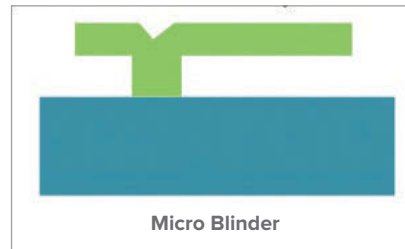
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