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TECHNOLOGY AND APPLICATIONS OF LIGHT EMITTING DIODES

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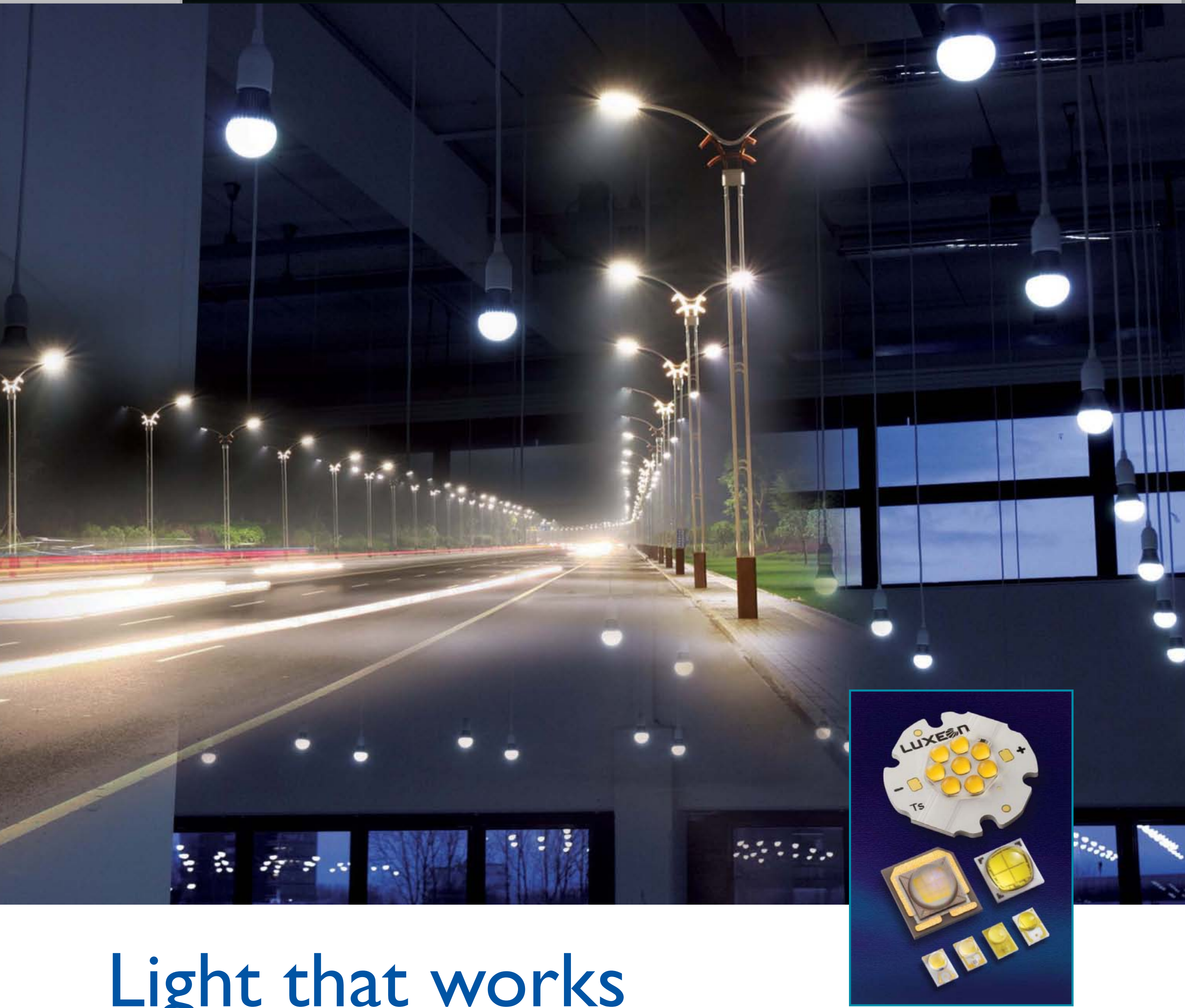

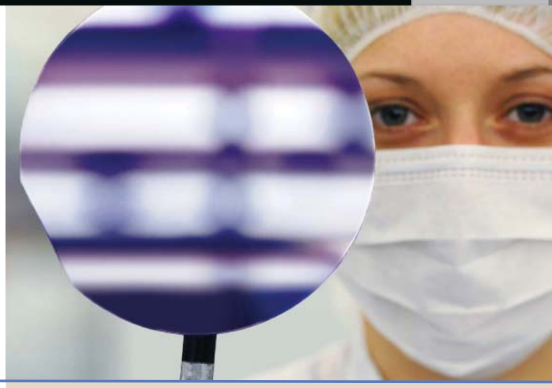

LEDs MAGAZINE® ISSUE 49

february 2012

Cover Story

GaN LEDs fabricated on large silicon substrates offer the promise of lower-cost manufacturing...if high device performance can be achieved. See page 9. Photo courtesy of Osram Opto Semiconductors.

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commentary

Uncertainty remains the order of the day

If you're reading this at Strategies in Light (February 7-9 in Santa Clara, CA), you may already have heard the latest LED market forecast from Strategies Unlimited, which will give everyone a much clearer idea of where the industry is heading. Compared with over 100% growth year-on-year in 2010, last year was relatively slow and it seems likely that the total market growth in 2011 was under 10%. Rapid installation of LED production capacity, built to serve the display-backlighting market, and lower-than-expected sales of TVs, have contributed to an "aggressive pricing environment," to quote Cree's latest quarterly report (www.ledsmagazine.com/news/9/1/20).

Chuck Swoboda, Cree chairman and CEO, also described the current business environment as "challenging" but spoke about the need to expand LED lighting adoption, because "adoption expands the market for both Cree and our customers." He said that Cree's belief is that "innovation drives payback, [and] payback drives adoption."

On the subject of adoption, the European Commission (EC) believes that Europe is lagging behind other regions and countries, and feels that the situation requires "immediate action." The EC has published its long-awaited Green Paper on solid-state lighting (page 33), which includes a consultation period for interested parties to offer comments and suggestions. The document recommends various policies and initiatives to continue the transformation of the lighting market to LEDs, while also strengthening the European lighting industry.

Few people doubt that the LED lighting market will continue to expand, but many may have been surprised over the last few months to see LED lamps and luminaires using lower-cost LEDs that were originally designed for the backlighting market, and are not optimized for lighting. In sharp contrast is Cree's new XB-D LED (page 14), which has a very small footprint (2.45 x 2.45 mm) and is intended to boost the amount of lumens per dollar that lighting-system integrators can achieve. Many other examples are available from other LED makers.

LED cost reduction is a major factor that will continue to influence LED-lighting adoption, as part of the bigger picture of lifetime costs and payback. Moving LED production to larger wafer sizes is a traditional way to reduce costs. Interestingly, Cree is decelerating its conversion from 100-mm to 150-mm wafers, in order to get the most from its factory in the short term by boosting its utilization rates. Low rates of capacity utilization are a feature of many LED fabs at the present time.

Cree makes GaN-based LEDs on silicon-carbide substrates, while most other LED makers use sapphire. Meanwhile, silicon substrates could offer significant cost savings if LEDs can be fabricated on large (at least 200-mm) wafers with performance and yield that matches current production devices. Although not the first LED maker to reveal details of its efforts to grow GaN-based LEDs on silicon, Osram Opto Semiconductors has made good progress and may introduce commercial products within around two years (page 9). Hopefully, some certainty will have returned to the LED market by then.

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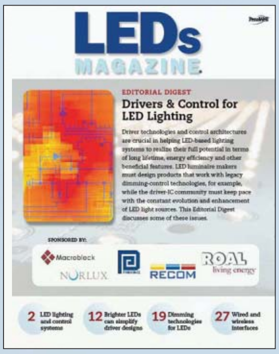

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Strategies in Light Europe

Strategies in Light Europe 2012

September 18-20

Munich, Germany

The Call for Papers for Strategies in Light Europe 2012 is now open, with a deadline of February 17. Abstracts should be submitted via the online form on the conference website. Papers submitted should describe or demonstrate:

- Efforts to improve the quality and performance of LED lighting
- Activities that help accelerate the market adoption of LED lighting
- Results from real-world LED lighting applications and installations

Strategies in Light Europe is in its third year of providing a comprehensive conference and exhibition for the rapidly-growing LED lighting industry. Papers will be selected by the SIL Europe Advisory Board on the basis of technical content, audience interest and industry relevance. Papers with overt marketing- or sales-related themes will be rejected. Suggested subject areas and themes can be viewed at www.ledsmagazine.com/features/8/12/6.

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LED CHIPS

Osram Opto unveils R&D results from GaN LEDs grown on silicon

Osram Opto Semiconductors has reported a set of R&D results from LEDs fabricated using gallium nitride (GaN)-based layers deposited on silicon. The R&D devices made using GaN-on-Si material have performance levels that are similar to production devices fabricated on sapphire.

Most GaN-based LEDs are grown on sapphire or silicon carbide substrates. While Osram Opto has already started moving its standard production of GaN-based LEDs to 150-mm (approx 6-in) diameter sapphire substrates (www.ledsmagazine.com/news/8/3/6), the real prize in moving to production on silicon wafers would be the opportunity to use larger (200-mm and above) substrates with much lower cost than sapphire.

"Our investments in years of research are paying off, because we have succeeded in optimizing the quality of the GaN layers on silicon substrates to the point where efficiency and brightness have reached competitive market levels," said Peter Stauss, project manager at Osram Opto Semiconductors. "Stress tests we've already conducted demonstrate the high quality and durability of the LEDs, two of our traditional hallmarks."

Using GaN-based material layers grown by MOCVD on silicon, die were fabricated using Osram's thin-film UX:3 process, which involves transfer to a silicon carrier and removal of the original silicon substrate.

Blue UX:3 chips in the standard Golden Dragon Plus package achieved an optical power of 634 mW at 3.15V, equivalent to 58 percent efficiency. These are very good values for 1-mm^2 chips at 350 mA.

In combination with a conventional phosphor converter in a standard housing, prototype white LEDs » page 10

BUSINESS

Philips Lumileds appoints Pierre Yves Lesaicherre as new CEO

LED maker Philips Lumileds has appointed Pierre Yves Lesaicherre as its new CEO. Lesaicherre will report directly to Philips Lighting's acting CEO Frans van Houten and takes the reigns in place of the retiring Michael Holt, who has led Lumileds for more than a decade since its inception. Holt is "retiring to enjoy more time with his family," said Van Houten.

Lesaicherre comes to the position after more than 20 years of experience in the semiconductor industry. "Pierre Yves' tremendous experience at NXP Semiconductors, most recently as senior vice president and general manager of microcontrollers and logic, make him uniquely qualified to lead Philips Lumileds into the new world of lighting," said van Houten. "I'm confident Pierre Yves will drive Philips Lumileds' performance and actively shape the fast-changing LED illumination market."

Lumileds Lighting was formed in 1999 as a joint venture between Philips Lighting and Agilent Technologies, a Hewlett-Packard spin off with LED expertise. Philips acquired a controlling interest in 2005. ◄

MORE: www.ledsmagazine.com/news/9/1/12

LED FABRICATION

SEMI forecasts reduced MOCVD purchases in 2012

SEMI, the semiconductor industry association, has released its latest Opto/LED FabWatch and Forecast report. The report predicts an 18% decline in overall worldwide spending on LED manufacturing equipment in 2012, and a 40% decline in spending on MOCVD systems. However, the report does indicate a positive side to the business: spending for non-MOCVD equipment, including lithography, etch, test and packaging equipment, will increase in 2012, as manufacturers balance their production lines with the significant MOCVD purchases from 2011. China is expected to be the largest spender this year at $719 million, followed by Taiwan ($321M), Japan ($300M) and Korea ($260M).

In terms of manufacturing capacity, Taiwan will continue to lead, with an estimated 25% of the worldwide LED capacity, followed by China at 22%. SEMI expects worldwide LED manufacturing capacity to reach two million wafers in 2012 (4-inch equivalent per month), a 27% jump over 2011. This is » page 10

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produced 140 lm at 350 mA with an efficiency of 127 lm/W at 4500K.

While these are R&D results, Osram says that the new LED chips are "already in the pilot stage," adding that its first LEDs fabricated on silicon could hit the market in around two years.

"For these LEDs to become widely established in lighting, the components must get significantly cheaper while maintaining the same level of quality and performance," said Strauss. "We are developing new methods along the entire technology chain for this purpose, from chip technology to production processes and housing technology."

Mathematically speaking, it is possible to fabricate over 17,000 1-mm^2 LED chips on a 150-mm wafer, more than twice as many as on a 100-mm wafer. Larger silicon wafers could increase productivity even more; researchers have already demonstrated the first structures on 200-mm (approx. 8-inch) substrates.

LEDs Magazine spoke with Strauss and Ulrich Steegmueller, Osram Opto's chief technology officer, who will discuss this and other subjects in his presentation at Strategies in Light 2012. "About three years ago we began a research project looking at the MOCVD growth of GaN on silicon," said Steegmueller. "At that stage it was very unclear whether the technology could approach similar levels to GaN-on-sapphire growth."

Initially, Osram Opto worked with Azzurro Semiconductors (www.ledsmagazine.com/news/6/11/16), another German company, using technology developed at, and transferred from, the University of Madgeburg. Recent work carried out internally by Osram Opto has been funded in part by the German Federal Ministry of Education and Research as part of its "GaNonSi" project network.

"We started initially on 2-inch silicon, and quickly moved to 4 inch," said Strauss. "Of course, we have moved to 150-mm manufacturing on sapphire in production, and our latest GaN-on-Si results are on 150-mm wafers. The eventual goal will be to move to 200-mm silicon or larger, which would be very difficult using sapphire."

The biggest challenge is successful MOCVD growth of the GaN-based layers. This requires complex stress engineering within the structure to overcome the difference in the thermal expansion coefficients of the different materials. Homogeniety and uniformity of the MOCVD-grown structure is very important, in order to make full use of the larger wafers and ultimately to achieve high yield in production. Steegmueller said that the uniformity is similar to material grown on sapphire.

Since silicon absorbs the emitted light, the substrate must be removed after growth. Thin-film LED structures are widely used by Osram Opto, and while the actual technology for removing the substrate is different for sapphire and silicon, the overall processes are compatible. Steegmueller points out that, because a thin-film approach (as opposed to wafer bonding to a carrier) is preferable, this creates a barrier to entry to companies that are not already working with thin-film structures. ◄

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largely due to last year's increase in equipment spending of 36% relative to 2010.

"Future equipment and capital spending will drive LED cost reduction through larger wafers, automation and dedicated equipment specifically designed to improve LED manufacturing yield and throughput." said Tom Morrow, executive VP, Emerging Markets Group, at SEMI. Twenty-nine new LED fabs opened in 2011, said SEMI, which predicts that a further 16 new fabs will come online during 2012. ◄

MORE: www.ledsmagazine.com/news/9/1/6

OLEDS

OLED research team wins German innovation award

Three founders of Novaled AG – Karl Leo, Jan Blochwitz-Nimoth and Martin Pfeiffer – have been presented with the Deutscher Zukunftspreis 2011 prize by the German Federal President Christian Wulff. The annual award honors creative teams for realizing breakthrough achievements in science and subsequently commercializing the technology. It comes with a prize of €250,000.

The team received the award in Berlin for their combined achievements in researching, developing and commercializing OLED technologies. Wulff stated that "the topic of this team is particularly promising because it really can make happen the energy turnaround [towards green energy]."

While at the Technical University of Dresden (TU Dresden), the researchers developed OLED technologies able to radically reduce the energy consumption of an OLED product. Currently, Karl Leo is Professor of Opto-

Electronics at the Institute of Applied Photo-Physics at TU Dresden and Director of the Fraunhofer Institute for Photonic Microsystems (IPMS); Jan Blochwitz-Nimoth is Chief Scientific Officer of Novaled; and Martin Pfeiffer is Chief Technology Officer of Heliatek, a producer of organic solar cells. ◄

MORE: www.ledsmagazine.com/news/8/12/17

MARKETS

Taiwan remains top LED manufacturer

Taiwan's LED industry remained the world's largest by revenue in 2011, according to estimates from the country's Photonics Industry & Technology Development Association (PIDA). According to an article on the Taiwan Economic News website (http://news.cens.com/cens/html/en/news/news_inner_38779.html), PIDA estimated that the 2011 revenue was US$4.53 billion. This figure

is down slightly (0.4%) from 2010 levels.

PIDA estimated that the second largest region, South Korea, had LED revenues of US$3.35 billion in 2011, up 5% from 2010.

PIDA said that South Korean LED manufacturers have "vigorously branched out into the lighting sector with low-priced products," but they lack the production scale to compete effectively with Taiwan's manufacturers.

Companies from the two countries compete strongly in the areas of LED epi-wafers and packaged LEDs. They are also starting to compete in LED street-lighting applications, propelled by optimistic roll-out plans being implemented by the federal governments in both Taiwan and South Korea.

PIDA says that the global LED industry had an estimated total revenue of US$16.6 billion in 2011, up 2.6% from 2010. The fastest growth was seen in mainland China, with 26% growth, while the market in Europe fell by 7.3% to US$1.6 billion. ◂

PATENTS

LED lawsuits and licensing

Intellectual property (IP) remains a key issue within the LED and solid-state lighting industry, and recent weeks saw a number of announcements that included both licensing agreements and further disputes revolving around patent infringement.

Seoul and Philips: Seoul Semiconductor Co., Ltd., has settled its LED patent dispute with Royal Philips Electronics and the two companies have entered into a cross-license agreement covering patents related to specific LED technology areas (www.ledsmagazine.com/news/8/12/4). The dispute stems from May 2011, when Philips' lawsuit against Seoul was quickly followed by news of counter-actions by Seoul against Philips. Under this arrangement, each party gains access to a substantial part of the other party's patent portfolios, said Seoul. Terms of the agreement were not disclosed.

Cree licenses remote-phosphor IP: Five LED lighting manufacturers – Aurora Energie, Horner APG, Ledzworld Technology, Vexica Technology, and Wyndsor Lighting – have licensed Cree patents that are critical to making remote-phosphor SSL products (www.ledsmagazine.com/news/8/12/24). These are the first deals under Cree's remote-phosphor licensing program that was announced in August 2011 along with the XLamp XT-E Royal Blue LED that targets such applications (pictured). According to George Brandes, Cree's director of IP licensing, the basic patent in the portfolio covers the generation of white light using a blue LED and a phosphor. He said other patents address geometric elements such as the distance between source and remote optic, the remote-phosphor structure, and how to design the cavity or mixing chamber. Cree believes that the IP portfolio is sufficiently broad that any luminaire maker designing a remote-phosphor-based lighting product may ultimately require a Cree license.

Mitsubishi Chemical and Intematix: Mitsubishi Chemical Corp. (MCC), the Tokyo, Japan-based phosphor, LED and lamp manufacturer, has filed a patent-infringement lawsuit in Korea against US-based Intematix Corporation and a Korean distributor, GVP. The lawsuit seeks to prohibit the two companies from importing and selling certain red-emitting phosphor products in Korea (www.ledsmagazine.com/news/8/12/25). The patent in question, no. 816693, relates to a nitride-type red phosphor with the formula $CaAlSiN_3$:Eu. The patent covers LEDs, lighting equipment, and other products in which the phosphor is used. In response, Intematix described MCC's patent-infringement claims as being "entirely without merit," and said that it intends to commence an invalidation proceeding against MCC.

Everlight and Nichia: Tawian-based LED maker Everlight has filed an unfair competition lawsuit in the Tokyo District Court against Nichia, a Japan-based rival (www.ledsmagazine.com/news/8/12/15). Everlight says that it has "decided to fight back" against Nichia, claiming that Nichia has "affected fair competitive market mechanisms" by filing lawsuits that Everlight describes as "baseless." In October 2011, for example, Nichia filed lawsuits against a

Japanese distributor of Everlight's LED products. LED patent disputes between Everlight and Nichia date back to 2006.

ATG and Philips: LED lighting manufacturer ATG Electronics Corporation recently joined Philips' LED Luminaires and Retrofit Bulbs licensing program, giving ATG access to basic system and control technologies for LED luminaires and retrofit bulbs (www.ledsmagazine.com/news/8/12/15). ATG also recently received multiple utility patents and a design patent in China for its LED products.

Dominant and Osram: *LEDs Magazine* recently reported that a German court had ruled in favor of Osram in its patent-infringement lawsuit against Dominant, a Malaysian LED manufacturer. However, according to Dominant's version, the court rejected 10 of the claims made by Osram (www.ledsmagazine.com/news/8/12/15). Dominant also says that the infringement confirmed by the court only relates "to product lines that have been terminated since 2004/2005 due to ongoing improvements."

GE and Dongbu Lightec: GE Lighting Solutions has settled a patent infringement lawsuit against Dongbu Lightec, formerly Fawoo Technology, of South Korea (www.ledsmagazine.com/news/8/12/26). The suit alleged that Dongbu Lightec's products infringed US patents no. 6,799,864 and 6,787,999 that cover LED lamp heat-sink designs, and systems and methods for efficiently replacing existing lamps with such designs. Dongbu Lightec has agreed to license GE Lighting's patents, while other terms of the settlement remain confidential.

OLEDWorks and GOT: OLEDWorks and Global OLED Technology (GOT) have signed a royalty-bearing patent license agreement, which grants OLEDWorks the right to use certain GOT patents in connection with the production of OLED lighting-related products (www.ledsmagazine.com/news/8/12/15). Michael Boroson, CTO of OLEDWorks, said, "We are very pleased to have access to this important patent portfolio. We believe that the technology developed at Kodak and now owned by GOT offers a superior approach for OLED lighting." ◂

TESTING

CSA opens new testing labs

CSA International has expanded its laboratory capabilities in Guangzhou, China, and has opened a new testing and certification laboratory in Atlanta, GA. In Guangzhou, CSA has added energy-efficiency verification (EEV) testing equipment to its existing LED lighting test and certification services. The Atlanta facility can certify LED and lighting products to 75 standards including Energy Star testing. "The expansion of the Guangzhou lab further demonstrates CSA's continued commitment to expanding operations in Asia to provide its clients [with] highly sophisticated and innovative

news+views

localized testing and certification services for global markets," said Ash Sahi, president and CEO of the CSA Group. ◂

MORE: www.ledsmagazine.com/news/9/1/17

LEDS

Cree aims to reduce system cost with XLamp XB-D LED

Cree has unveiled its new XLamp XB-D LED family, with a 2.45×2.45-mm footprint, which the company says will deliver double the lumens per dollar achievable at the system level. The small footprint (Cree's XM-L has a footprint of 5.0×5.0 mm) will be especially suited to SSL retrofit lamps, although Cree has said the LEDs will serve a broad application base. At 350-mA drive current and 85°C operating temperature, the new LED platform delivers 139 lm at 6000K and 107 lm at 3000K. The efficacy is 136 and 105 lm/W, respectively. Maximum drive current is 1A. A notable feature according to product marketing manager Paul Scheidt is the fact that the XB-D family is the first to be hot-binned across all CCTs. He said, "Competitors only hot bin in the warm-white CCTs."

The new platform is designed to reduce system cost. The smaller die has a direct impact on component cost because Cree can manufacture more components per wafer. The smaller footprint also provides designers of retrofit lamps with far more flexibility in lamp design. For example, Scheidt showed an example of a standard A-lamp where the LEDs can be placed deeper in the neck of the lamp rather than at the equator of the globe, thereby providing better light distribution. He added that the smaller size simplifies the design of optics, reflectors and circuit boards, further reducing cost.

The company is using new die architecture and packaging schemes, including a beveled structure around the die designed to maximize light extraction. Cree uses a flip-chip approach in which the substrate side of the die is on the top side of the packaged LED. Scheidt said that Cree's SiC substrate offers a refractive index that better matches the GaN layers than does sapphire, thereby improving light extraction. Scheidt added that SiC offers a better match in coefficient of thermal expansion, resulting in fewer cracks.

With the XB-D LED, Cree aims to increase the penetration of LED lamps in price-sensitive markets. "The product itself is there in terms of technology. People accept it," Scheidt said, referring to aspects such as color and light quality. In terms of current price levels, he stated, "We're at least in the right order of magnitude." ◂

funding + programs

US spending bill delays lamp-efficiency enforcement

US President Obama signed a $1 trillion spending bill into law on Dec 23, 2011, which included a rider affecting the light-bulb efficiency legislation that subsequently took effect on Jan 1, 2012. The rider didn't change the law requiring more-efficient lamps, but eliminated funding that the US Department of Energy (DOE) would have used to enforce the legislation.

There were widespread reports in December that the rider would eliminate the lamp-efficiency elements enacted in the EISA (Energy Independence and Security Act) 2007 legislation, which have been incorrectly referred to as a ban on incandescent light bulbs. In reality, the rider simply affects enforcement (www.ledsmagazine.com/news/8/12/18). The rider applies through Sept 2012 and no one knows if Republican legislators will attempt to extend the funding cut beyond the scope of the new spending bill.

The real question now is what if any impact the rider will have. Starting in 2012, the EISA 2007 legislation requires that lamps with 1700-lm output, which is typical of 100W incandescent lamps, deliver 30% greater efficiency. Traditional incandescent lamps can't meet those guidelines. LED-based and compact-fluorescent lamps are certainly viable options. The major lighting companies also have developed new hybrid incandescent/halogen lamps that can meet the requirements.

The major lighting companies will certainly comply with the legislation on the books. Back in December, Joseph Higbee, director of marketing communications at NEMA (National Electrical Manufacturers Association), said, "The standards are the law and the manufacturers will follow the law." The IES (Illuminating Engineering Society) has also posted a statement (www.ies.org/pdf/PublicPolicy/Update-Incandescent-Lamp-Regulations.pdf) in the public policy section of its website that concludes "Bottom line: the law is still in effect – nothing has changed in that regard."

The legislation never prohibited stores from selling lamps it had in stock, but prohibits import and US-based manufacturing of inefficient lamps. Policing imports could be a problem.

Indeed it could be that the major lighting companies that have invested heavily in meeting the efficiency requirements are worried about importers that flaunt the law. That's the theory of Matt Mitchell, an economist and senior research fellow at the Mercatus Center at George Mason University. According to Mitchell, the major lighting companies don't want the legislation repealed or enforcement delayed. In his Neighborhood Effects blog, he suggested that the leaders fear that smaller competitors that haven't invested in more-efficient designs will use the enforcement delay to ship older incandescent lamps into the US.

No one has suggested that major US retailers will import lamps that violate the legislation. However, even with enforcement funding in place, the Internet and online commerce would have likely made it easy for consumers to buy standard incandescent lamps. The lack of DOE funding will probably increase the volume of such sales. ◂

DOE study finds no LED replacement for post-top street lights

The US Department of Energy (DOE) has published a report from a demonstration of LED technology in ornamental post-top street lights. Among four different LED replacement products, none could match the performance or cost of the existing 100W high-pressure sodium (HPS) fixtures (www.ledsmagazine.com/news/9/1/15). The four LED replacement products were evaluated using computer simulations, field measurements and laboratory testing. The evaluation was conducted by DOE's Municipal Solid-State Street Lighting Consortium (MSSLC) in collaboration with the Sacramento Municipal Utility District and the City of Sacramento, with additional support from City consultant Mary Matteson Bryan.

This study was restricted to lamp-ballast retrofit kits and complete luminaire replacements that would preserve the daytime appearance of the existing acorn-style luminaires. To allow for apples-to-apples economic comparison, the pricing and input power of the LED products had to be scaled proportionately to represent hypothetical products which could match light levels from the HPS fixtures. Energy used by three of the scaled-up LED systems ranged from 63-90% of the baseline HPS. The fourth product would actually require an increase in energy use by 15%. None of the products would represent cost-effective alternatives to HPS.

In response to recent industry developments, the study further investigated the relative significance of mesopic multipliers offered in the new IES Lighting Handbook and the lumen-maintenance extrapolation methodology offered in the new IES TM-21.

This is the first of a series of projects the MSSLC will conduct to serve as objective resources for LED product evaluations and a repository for valuable field experience and data. ◂

funding+programs

LEDs shed new light on social housing

A field trial involving the LED replacement of over 4000 light fittings in England determined that LED lighting can deliver significant reductions in energy and maintenance cost while providing improved brightness, color and distribution in communal areas of public housing. The study, by the Energy Saving Trust (EST), a not-for-profit energy-efficiency organization, estimated that ongoing energy savings would be over 3 million kWh annually.

The EST first performed a feasibility study in 2008 that looked into installing LED lighting in communal areas of social housing, such as stairwells and corridors (see photo, with LED retrofits in place). The study indicated that there was considerable potential for achieving energy savings, particularly as the lighting is typically on 24 hours per day. Estimates indicated that the LED lighting would pay back its original investment cost in two years.

The resulting field-trial report showed increases in light levels, color temperature and good maintenance of performance over time, as well as considerable energy and long-term cost savings. The first phase of the trial, which ran in 2008-09, saw a 100% average improvement in illuminance (lux) levels across the sites, with two buildings showing illuminance improvements of over 500%. The second phase of the trial, in 2009-10, featured a greater number of individual light fittings and also saw an increase in illuminance levels of 57%.

The incumbent lighting had a warm-white average CCT of 3344K, while the LEDs provided a cooler average CCT of 5086K, much closer to that provided by natural daylight.

James Russill, the EST's technical development manager, said: "This trial has shown that the technology is performing to a high standard. In terms of social housing this represents a great opportunity to overhaul the look and feel of the places people live and also reduce costs at the same time."

When the trial began in 2008, the lack of off-the-shelf light fittings would have significantly impacted the payback time for installing LED lighting. However, in the course of the study, rapid development in LED technology led to the availability of off-the-shelf fittings from several UK manufacturers suitable for direct retrofit.

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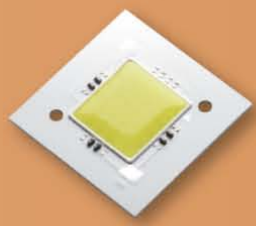


standards | **UPDATE**

Lumen-maintenance testing for LED lamps, light engines and luminaires

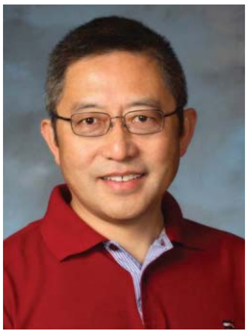
Now that procedures are in place to make long-term lumen-maintenance projections for LED components, efforts are being made to develop methods for testing the lighting system as a whole, as **JIANZHONG JIAO** explains.

It is widely understood that measuring lumen maintenance is critically important for determining the life of LED lighting products. In the past few years, the Illuminating Engineering Society of North America (IESNA) has developed two test methods that address the lumen maintenance of LED light sources used in such products. LM-80 is an approved method for measuring lumen depreciation of LED light sources, and TM-21 is a technical memorandum which specifies how to extrapolate the LM-80 data in order to make long-term lumen-maintenance projections.

Beyond the LED, other components at the LED lighting-system level also can impact the long-term lumen maintenance. These components include, but are not limited to, LED lamps, engines, luminaires, drivers, thermal-management devices and optical components. Over time, these components may experience some change or degradation. In particular, the plastic elements used in the optics may change in several ways, including light transmittance, haze and undesired color change. In turn, the overall light output of the LED lighting products will be further reduced beyond the normal lumen degradation of the LED source. Therefore, it may be necessary to conduct lumen-maintenance tests at the LED lighting-system level.

System-level testing

In 2010, the IESNA Testing Procedures Committee (TPC) formed a working group to draft a document to recommend the best methods for testing lumen maintenance of LED lamps, engines and luminaires. Because of the various ways of integrating LEDs into lighting systems, the TPC experts concluded that LED lumen-maintenance information obtained from LM-80 and TM-21 may not be sufficient to reflect the changes in a system's light-output level over time. This conclusion led to the direction of testing the lighting system as a whole.



Further, the performance of LED lighting systems is typically affected by variables such as operating cycle, ambient temperature, airflow, and orientation, as well as conditions imposed by auxiliary equipment and fixtures. These conditions are not accounted for in the LM-80 testing of LED sources. As a result, it may become necessary for the IES to provide recommendations on these test conditions, and test methods would need to be designed to give comparable results when adopted by various testing laboratories.

A lumen-maintenance test standard for LED lamps, engines and luminaires is still being developed, with multiple drafts created, and some preliminary balloting already completed. Different from the LM-80 test standard, this new document will address the tests that are more uniquely applicable to LED lighting systems, including temperature conditions, operational duty cycle and test duration.

For LED sources, LM-80 recommends three case temperatures at which testing is performed. Often, the LEDs being tested are placed in temperature-controlled thermal chambers with sophisticated active-cooling systems. These precisely set the LED case temperatures to meet test requirements, with each test running for a minimum of 6000 hours at each case temperature.

It can be cost-prohibitive and impractical to test entire LED light systems – such as large luminaires for outdoor roadway lighting fixtures or chandeliers for indoor lighting – in the temperature-controlled chamber for long periods of time. Instead, the TPC recommends LED lighting systems be tested in a condition as close as possible

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to the installation orientation and mounting method, which in many cases is room temperature (25°C) with tolerances.

The temperature-control points for the room environment where LED lighting systems are placed in the burning cycle, or the period of time when LEDs are turned on, may need to be monitored. This provides a more practical and flexible situation for test labs or manufacturers to conduct tests, either in designated test rooms or within enclosures where the LED lamps, engines and luminaires are mounted. Understanding that ambient temperatures may affect long-term lumen output for the LED lighting systems, the TPC recommends that the tested samples be mounted in accordance with manufacturer recommendations, taking unintended thermal dissipation into consideration.

LINKS

The elusive "life" of LEDs: How TM-21 contributes to the solution
LEDs Magazine Nov/Dec 2011, p37; www.ledsmagazine.com/features/8/11/10

Understanding the difference between LED rated life and lumen-maintenance life
LEDs Magazine Oct 2011, p51; www.ledsmagazine.com/features/8/10/12

Cycling

Also of concern is the operational duty cycle. When testing LED sources per LM-80, the samples are consistently powered on throughout the test. In practice, however, LED lighting systems are cycled on and off in almost all applications for both indoor and outdoor lighting. As has been demonstrated in the past, cycling lamps on and off has an impact on lamp life for other lighting systems such as high-intensity-discharge (HID) and fluorescent lamps.

Although cycling may not have as dramatic an impact on LEDs, the driver electronics can be affected. Therefore, the TPC recommends that the burning cycle during lumen-maintenance testing should not be conducted in a constant on condition. Instead, the TPC specifies an operational cycle with certain periods of on time and off time. This cycling condition is intended to have a closer relationship to real-life LED system applications.

Test duration

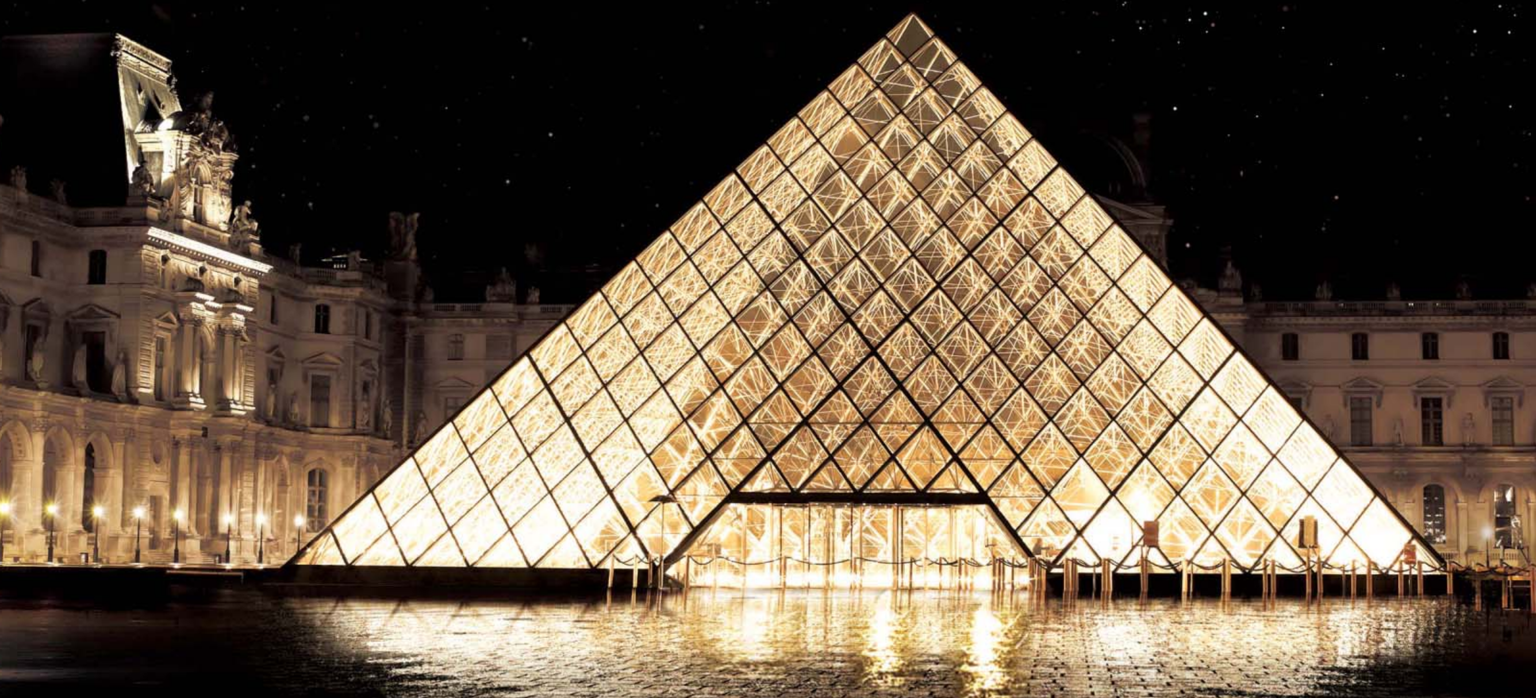
The duration of testing is another variable to consider, and the area where experts have struggled the most to establish a standard. It is clearly understood that lumen maintenance over time usually cannot be detected over a short testing period. LM-80 specifies a minimum of 6000 hours of testing.

However, for LED systems, including lamps, engines and luminaires, prolonged testing creates a large burden for manufacturers and the lighting industry. Any recommended testing procedure from the IES must present practical values for the duration of testing. A testing period that is too short may not lead to conclusive characteristics being identified. On the contrary, as stated above, a testing period that is too long may create an unsustainable burden.

Without standardization of the test duration and with incomplete testing methods, the industry could suffer from inconclusive test results. The discussions on testing duration are still taking place in the TPC working group, and there are several specific suggestions currently under consideration.

One suggestion is to specify certain testing durations to the users of the document depending on what information users are looking to determine. In other words, if the intent of the test is to identify LED lumen-maintenance degradation in the early stage of usage, the samples may be tested for 2000 hours. If the intent of the test is to use the collected photometric data to make long-term lumen-maintenance projections, the samples may be tested a minimum of 20% of the specified lumen-maintenance life. In doing so, the test data may apply as with the TM-21 memorandum. If the test is meant to obtain the actual lumen-maintenance life for the LED products, the samples should be tested for the entire claimed lumen-maintenance life.

It is expected that a new testing standard will provide significant value to the SSL industry. In a broader sense, consistent, objective and practical testing methods recommended by the IESNA are necessary for the implementation and adoption of SSL technologies, both for government or consortium specifications, as well as for industry product-performance standards.



Are you using all of the lumens that you paid for?

The latest LEDs can reliably operate at drive currents well above binning currents, delivering more lumens and robust luminaire life while lowering system cost, explain **DAVID COX**, **DON HIRSH**, and **MICHAEL McCLINTIC**.

In the evolution of the microprocessor there have always been uses for faster, more powerful or more compact processors. Historically, with each new generation of microprocessors, electronic devices would in turn become more sophisticated, smaller, faster, and/or cheaper. LED efficacy has been improving similarly to the evolution of the microprocessor, but LED-based illumination designs are not consistently taking advantage of capabilities such as brighter operation at higher drive currents. Today, luminaire manufacturers may find that the surest path to lower system cost is to take advantage of the full LED operating capacity or lumen output that they are already paying for while relying on the growing statistical evidence that they can do so and deliver long product life.

Advances in the production of lighting class, high power LEDs should cause the lighting industry to reassess how to create cost-optimal, LED-based designs. Several advanced LED manufacturers, Cree included, have developed a large and expanding body of information concerning performance maintenance of LEDs over time and temperature. This knowledge of long-term behavior is now standardized in LM-80 data sets that track lumen maintenance and color shift and in TM-21 projections of that performance over longer time periods. See www.ledsmagazine.com/features/8/11/10 for details on TM-21 methodology.

For Cree, the data shows, in the highest quality parts and in well-designed systems, that LEDs can operate at high current and high temperature levels with fewer performance penalties than ever before. This same data calls into question legacy luminaire and driver design methodology that has yielded systems that drive the LEDs around binning-current levels rather than over a wide range of drive currents and temperatures.

Using LEDs at higher operating capacity can deliver more lumens per LED with a corresponding reduction in system cost. For many lighting applications, more aggressively priced products can be created with reduced component count. Such a design methodology can result in higher operating temperatures and lower efficacy. Still, taking full advantage of an LED's operating capacity becomes an attractive option for applications requiring maximum lumen output at a reduced cost.

Current	Ta/Tsp	Test Duration	α	β	Calculated L70	Reported L70
1000 mA	55°C	10,080 hrs	-4.219E-06	9.847E-01	---	L70 (10k) > 60,500 hrs
1000 mA	85°C	10,080 hrs	1.284E-06	1.016E+00	290,000 hrs	L70 (10k) > 60,500 hrs
1000 mA	105°C	6,048 hrs	5.561E-06	1.007E+00	65,500 hrs	L70 (6k) > 36,300 hrs

TABLE 1. TM-21 projection for Cree XLamp XP-G LEDs.

Unused operating capacity

Let's examine the potential of fully using the available LED operating capacity. Previously, a conservative design strategy was appropriate for a relatively young technology such as packaged, high-power LED components. Fig.1 represents that approach at the left side of the shaded area in the light-output/efficacy vs drive-current graph.

We now know more aggressive designs are desirable and appropriate for cost-efficient designs. For lighting-class LEDs, that is LEDs that maintain chromatic and luminous stability, there is an abundance of unused lumens available to thoughtful system designers. With operating temperature held constant, Fig. 1 shows the under-utilized LED operating capacity. When driven at binning current (350 mA), this LED is delivering less than 25% of its rated capacity. The other 75% is bought, paid for and under utilized.

Driving LEDs around the binning current has been both an industry-wide habit and an engineering-conservative approach to system reliability. But let's consider evi-

DAVID COX *is Sales Development Manager at Cree, Inc.* DON HIRSH *and* MICHAEL MCCLINTIC *are Product Marketing Managers in Cree's LED Components Business Unit.* *Thanks to* MICHAEL LEUNG *at Cree's Santa Barbara Technology Development Center and to the application engineering team at Cree's Shenzhen Technology Center for their work in developing and analyzing the two 6-inch downlights.*

dence showing that much more aggressive drive currents and temperatures are possible without sacrificing long-term reliability.

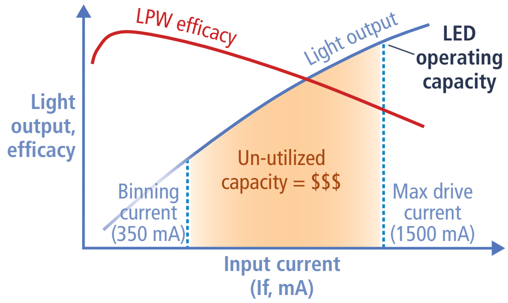


FIG. 1. The graph of light output and efficacy over current shows the under-utilized operating capacity for the Cree XLamp XP-G LED.

Reliability data and projections

LM-80 data sets used to create TM-21 projections are the reliable and standardized method that supports a prediction of a given LED's lumen maintenance in a system context. The methodology supports prediction of lumen maintenance at the specific operating temperature projected for the system design and application.

For example, take the 1000-mA LM-80 data and TM-21 projections developed for Cree's XLamp XP-G LED. At an operating temperature of 55°C – a realistic operating temperature for an indoor luminaire – the reported TM-21 L70 result, based on 10,080 hours of LM-80 data, is 60,500 hours. Since there has been no luminous degradation of the LEDs under the LM-80 tests a TM-21 L70 calculated value cannot be provided. At 85°C the L70 reported projection is still 60,500 hours while the L70 calculated projection is 290,000 hours. The 1000-mA drive current represents 67% of the 1500-mA max drive current of the XP-G.

Fig. 2 shows L70 LM-80 measured data and TM-21 reported-life projections over three different operating temperatures. TM-21 methodology supports interpolation for projections that fall at operating temperatures between those used in the LM-80 tests.

The relatively lengthy projections of L70 LED life (the operating time before the LED drops below 70% of its initial lumen output) even call into question the use of L70 as a demarcation of useful life. Indeed TM-21 projections reveal that state-of-the-art LEDs can be specified at higher lumen-maintenance levels while still delivering acceptable lifetimes. Consider the following TM-21 projections, based on 10,000-hour LM-80 data sets, for the XLamp XP-G LED driven at 1000 mA at an operating temperature of 85 °C. The L95 reported life is 52,100 hours and the L90 reported life is greater than 60,500 hours.

The concept of using higher drive current also applies to LED families other than the XP-G. For example, the XLamp XM-L family is rated for 3000-mA maximum drive current. At 67% of maximum rated drive current (2000 mA), the TM-21 L70 projections yield a reported value of 36,300 hours based on 6000 hours of LM-80 testing. That 36,000-hour reported result is gated by the LM-80 test time and is valid across the LM-80 temperature range. But the calculated projections range from 2.3 million hours (at 45°C) to 160,000 hours (at 85°C).

Color shift data

In addition to long lumen maintenance, the latest lighting-class LEDs also perform well in terms of color shift. The graph in Fig.3 depicts the color shift in the XP-G LEDs over time and at different operating

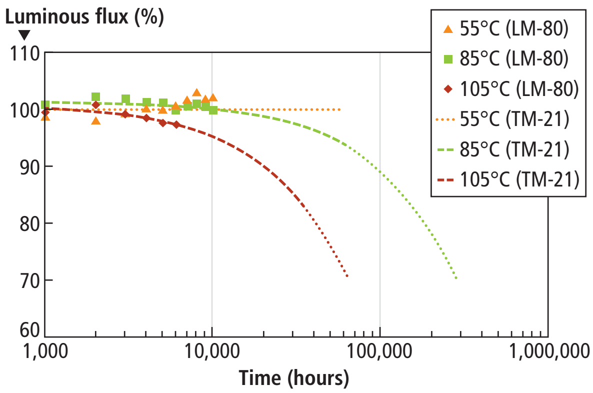
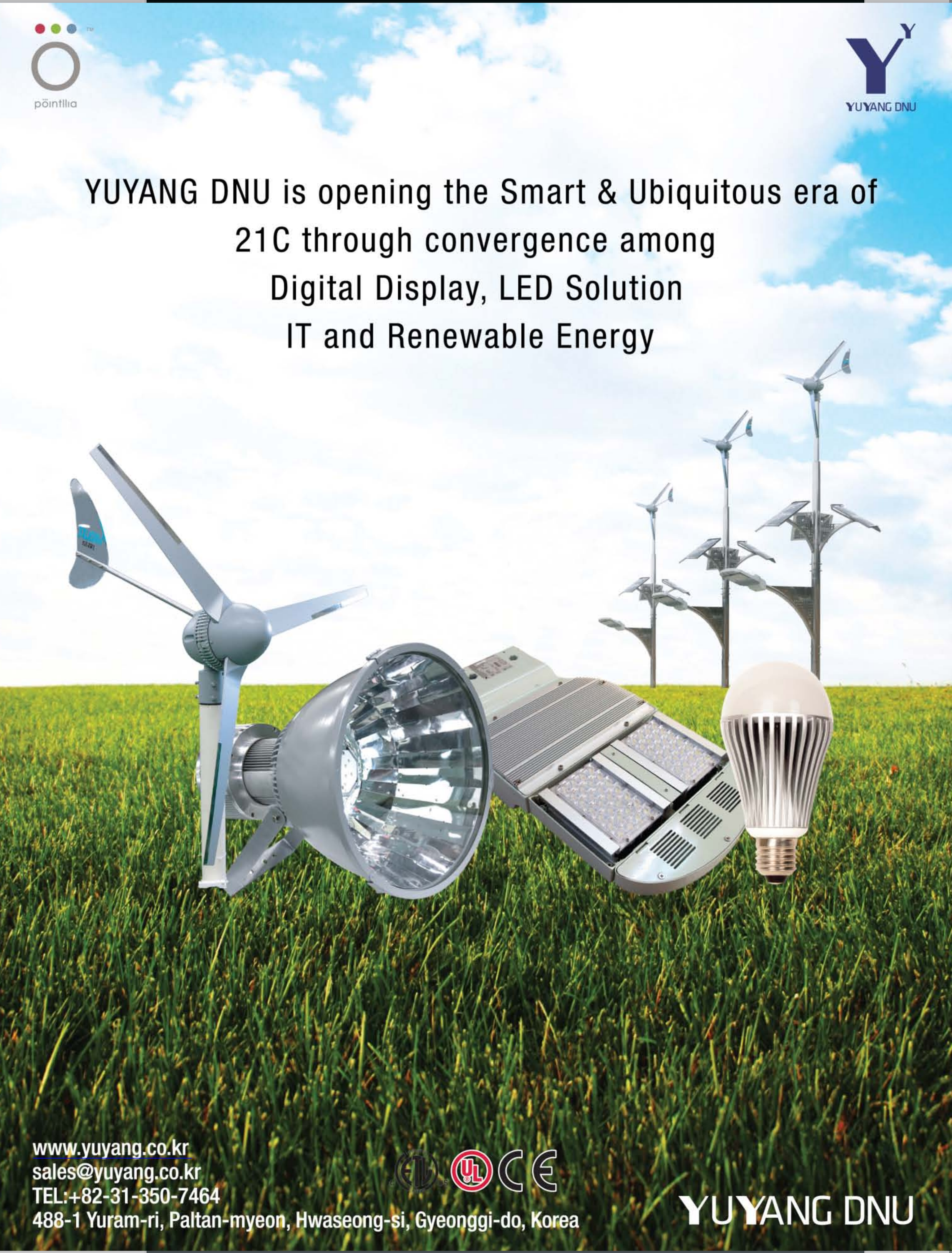


FIG. 2. A graphical representation of TM-21 L70 reported life projections for XLamp XP-G LEDs driven at 1000 mA.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temperatures. The family maintains shifts of less than 0.004 du′v′ in all cases.

Similarly, in 6048 hours of LM-80 testing the XM-L LEDs exhibited a du′v′ shift of just over 0.002 at 2000 mA and 45°, 55° and 85°C. Clearly, the XLamp XP-G and XM-L LEDs do not need to be driven at 350 mA, nor maintained at a low ambient temperature to achieve a long-lived, chromatically-stable system design.

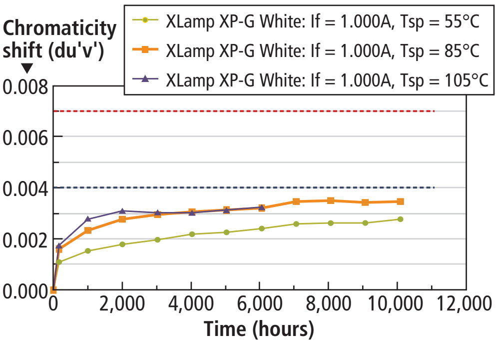
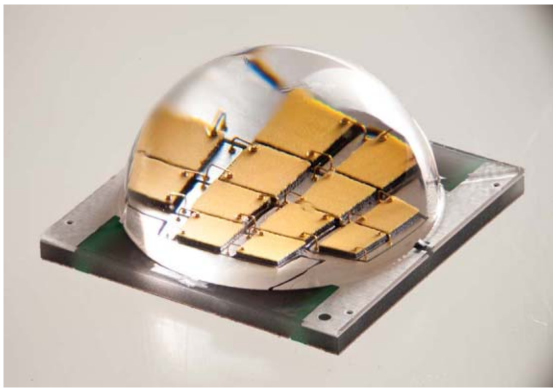


FIG. 3. LM-80 data shows minimal color shift in XP-G LEDs over time and different operating temperatures.



LED-based system design always requires the engineer to evaluate a series of tradeoffs between power consumption, operating temperature, and other elements such as efficacy and droop. The LEDs themselves exhibit quasi-linear performance in a number of their operating parameters. What's new in the progression of LED technology is that LEDs capable of higher-current operation make the optimization of the non-linear factors (such as droop and hot-cold operational differences) substantially less-pressing design concerns.

Analyzing tradeoffs

Characterization tools offered by LED manufacturers such as Cree can help the design team contemplate the tradeoffs, especially in terms of efficacy. Cree offers its online Product Characterization Tool (PCT) at http://pct.cree.com.

PCT shows that Cree's brightest cool-white, single-die LED components evaluated at a reasonable operating temperature of 55°C are all capable of delivering component efficacy well above 100 lm/W

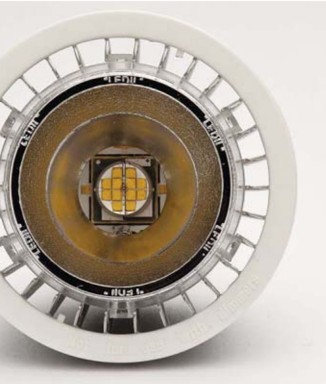


FIG. 4. Size constraints on a heat sink limit the drive current for an MT-G LED (top) in an MR16 lamp reference design (bottom).

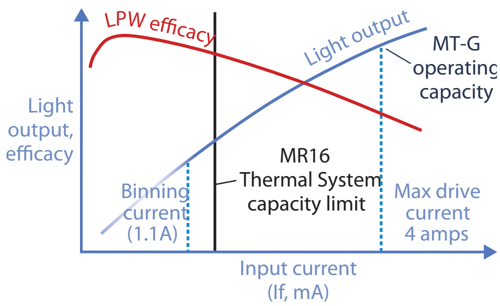


FIG 5. The MT-G LEDs in the MR 16 lamp must be operated near the binning current.

at elevated drive currents. Similarly with warmer phosphor mixtures, Cree's brightest warm-white, single-die LED components deliver 75-90 lm/W at 55°C, at drive currents well above the binning current.

LED component manufacturers, who provide engineering tools to perform system analyses, allow for rapid, basic performance assessment. When long-term performance and reliability data are available over a wide range of operating conditions, device and component-level non-linearities need not be important selection criteria. They are simply attributes of the devices to be taken into consideration during the design cycle. Long-term performance data at elevated currents and temperatures allows an assessment of whether there is a valid concern for a particular manufacturer's particular LED component under consideration.

While we've shown that driving LEDs at higher drive currents and/or elevated temperatures allows the designer to extract more lumens from each LED, there are practical constraints. The lamp or luminaire designer must consider issues such as thermal system design when looking to reduce LED component count and thereby also reducing costs. The following examples illustrate the system considerations.

System constraints

Cree's XLamp MT-G EasyWhite LED is a multi-die LED, optimized for high-output, small-form-factor, directional lighting applications. The maximum current rating for the MT-G is 4000 mA, a substantial 24W in a 9×9-mm package. But a small-form bulb, such as an MR16, cannot dissipate greater than 20W of thermal load. Fig. 4 depicts the LED alone and designed into an MR16 lamp design.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Characteristic	Unit	12-LED downlight	5-LED downlight	Energy Star requirements
Light output (30 min on time)	lm	943	930	
Current	mA	350	1000	
Power	W	14.5	19.2	
Efficacy	lm/W	65.0	48.4	42
CCT	K	3000	3020	3000
Driver efficiency	%	87	87	
Lifetime	hours	60,000	60,000	35,000
CRI		80.6	80.2	≥ 80
Tsp	°C	52	74	
Tj (calculated)	°C	~61	~90	

TABLE 2. A summary of operating characteristics for two 6-inch downlight reference designs.

Based on Cree's experience in building a MR16 reference design we found that heat sinks for the MR16-class LED sources could safely dissipate 4-7W of power. The geometry of the heat sink constrains the drive capacity of the LED system. Fig 5. shows that, in the case of an MR16 lamp, the LED must be driven relatively close to the binning current and far below the maximum drive current. The MT-G LED, when used with a larger heat sink – such as a heat sink to support a PAR38 bulb application with several times the mass of the MR16 heat sink – can support a much higher drive current.

Cree's Shenzhen Technology Center has developed other reference designs that illustrate the concept of LED operating capacity tradeoffs. Engineers built two 6-inch recessed downlight fixtures using Cree's XLamp XP-G LED. Using the same mechanical enclosure and heat sink, but different drivers and numbers of LEDs, we developed two systems with nearly identical light output, distribution, CCT and CRI. One design uses 12 XP-G LEDs being driven at the LED's 350 mA binning current while the other uses 5 XP-G LEDs driven at 1000 mA.

Table 2 summarizes the results. Though differing in efficacy, both downlights meet Energy Star efficacy, correlated color temperature (CCT) and color rendering index (CRI) requirements. In this example one can reduce the number of LEDs in a fixture by 60%, obtaining almost identical optical performance in exchange for an elevated, but still reasonable, operating temperature and reduction in system efficacy.

Note that in some cases Energy Star requirements can also limit the choice of drive currents. Efficacy is a key element in Energy Star and at some point a higher drive current in a particular system design could result in an efficacy spec below the Energy Star limits.

Generally, however, LEDs have far more luminous capacity than most designers are using. The highest quality LEDs are capable of operating at sustained, elevated currents and temperatures far above manufacturers' binning information. New luminaire and lamp designs should take advantage of these attributes. For lighting class LEDs, there is no reliability penalty for using more of this capacity.


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European Commission initiates public consultation on LED lighting

A Green Paper on LED- and OLED-based lighting published by the European Commission launches a period of public consultation on the future development of SSL in Europe, as **TIM WHITAKER** explains.

In late December, the European Commission (EC) published a Green Paper on LED- and OLED-based solid-state lighting (SSL) entitled "Lighting the future: Accelerating the deployment of innovative lighting technologies." The document proposes a number of new Europe-wide policy initiatives that are intended to accelerate the deployment of SSL in European Union (EU) member states. The Green Paper also encourages public debate in Europe involving all interested parties, which are listed as research and business stakeholders, governments, civil society communities and citizens.

The Green Paper's publication initiated a public consultation period, which ends on February 29, 2012. The EC is seeking the views of all interested individuals and organizations on the relevant issues involved, and will collect replies to specific questions that are set out in the Green Paper. Links to the Green Paper and the consultation documents can be found at www.ledsmagazine.com/news/8/12/19.

FIG. 1. Tungsram-Schréder has supplied over 6200 LED luminaires to replace all of the street lights in the Hungarian city of Hódmezővásárhely (www.ledsmagazine.com/news/8/12/23). However, such large-scale SSL deployments are relatively rare across Europe, a situation that the EC intends to address.

The Green Paper is part of the Digital Agenda for Europe initiative, under the Europe 2020 strategy that aims to stimulate "smart, sustainable and inclusive" growth (http://ec.europa.eu/europe2020). The policies related to SSL are designed to help achieve the key objectives of Europe 2020 relating to energy efficiency, industry and innovation.

SSL in Europe

The EC believes that, while Europe's lighting industry is both "large and world class," SSL market uptake is slow in Europe. The Green Paper says that the LED-based SSL accounted for 6.2% of the overall lighting market in Europe in 2010. However, several studies indicate that SSL will account for more than 70% of Europe's general-lighting market by 2020. This assumes that various market barriers can be removed to enable SSL to deliver its full potential.

The EC also says that SSL-related research, innovation and cooperative activities are fragmented in Europe. In this respect, Europe compares poorly with the USA and various countries in Asia. The situation indicates a need for immediate action at the European level.

First, the Green Paper addresses policies targeting European users (consumers, professional users and public procurers) that will help to overcome existing challenges and promote wider market uptake. This includes raising awareness of, and demonstrating, the benefits of SSL, as well as proposing initiatives to prevent early market failure.

On the supply side, the Green Paper proposes policies that "foster the competitiveness and global leadership" of the European lighting industry. This will, says the EC, contribute to the creation of growth and jobs.

Challenges and policies

Several specific challenges are indentified for SSL: products are expensive; users are unfamiliar with this new technology and need to develop trust in its use; the technology is subject to rapid innovation; and there is a lack of standards.

A number of policy instruments related to SSL – some voluntary, some mandatory – are already in place in Europe. Several of these were described by Paolo Bertoldi of the EC's

Joint Research Centre at last October's Strategies in Light Europe conference (www.ledsmagazine.com/features/8/11/8).

Perhaps best known is the Ecodesign Directive which has set minimum performance requirements for non-directional lamps (http://ec.europa.eu/energy/lumen/index_en.htm). This has already resulted in the phase-out of inefficient 60W-and-above incandescent lamps (www.ledsmagazine.com/news/8/9/1). The EC intends to adopt a new Ecodesign regulation that will cover directional light sources (e.g. reflector lamps), setting minimum functionality requirements.

The EC is also revising the Energy Labelling regulation for light sources, and intends to include LEDs and all kinds of directional and professional lamps. Energy labels are intended to allow end-users to choose more-efficient products by providing standard product information on energy consumption. Revised Ecolabel criteria are also under consideration; Ecolabel is a voluntary scheme to promote products with good environmental performance. A number of other instruments also apply to SSL, including the Low-Voltage Directive, and the directives on Restriction of Hazardous Substances (RoHS) and on Waste Electrical and Electronic Equipment (WEEE).

Of course, for these various policy instruments to be effective, they need to be effectively policed. As stated in the Green Paper, EU member states and the lighting industry need to ensure that SSL products sold in Europe conform to EU legislation on performance and safety requirements. An effective market-surveillance scheme is seen as a prerequisite for the uptake of high-quality LED products within the EU market.

Also, the Green Paper invites lighting stakeholders and/or consumer associations to organize awareness campaigns that help to increase user awareness of SSL products. Part of this activity is the need to make sure that various technical properties are explained properly on the product package, so that consumers can make meaningful comparisons.

Another potential barrier to SSL is related to concerns about biological safety, often described as "the blue-light hazard." For more on this subject, see our series of articles concluding on page 63 of this issue. The EC says that it will "continue to monitor developments" regarding potential effects of LED lighting technology on consumers' health.

SSL and Europe's lighting industry

The EC's Green Paper says that Europe's lighting industry employs 150,000 people, has an annual turnover of EUR 20 billion and is "highly fragmented along the value chain." The region hosts a number of major global companies as well as several thousand small and medium enterprises (SMEs), mainly at the luminaire level. Europe-based lighting giants Philips and Osram are also major LED manufacturers, although only Osram, Optogan and Tridonic have significant LED production capabilities in Europe. Europe is well positioned in the area of OLED lighting technology, but is struggling to convert its R&D expertise into business success.

As SSL achieves greater penetration into the general-lighting market, the nature of the lighting industry will change. Sales of retrofit lamps are expected to dominate the SSL market over the next 3-5 years, driven by the phase-out of inefficient incandescent lamps. But then the industry is likely to see a shift towards sales of luminaires, and in particular intelligent lighting systems and lighting services. Tailor-made lighting systems are seen as a growth opportunity for the lighting industry, where characteristics can be tailored to specific users' requirements, for example the needs of an aging population.

The changing business model for many lighting and luminaire manufacturers will require enhanced cooperation with an extended value chain. This will include, for example, architects, lighting designers, and suppliers of building-control systems, all areas where Europe has considerable strength.

Of course, the European lighting industry is already under considerable pressure, not least from Asian companies with expertise in LED display backlighting that are now entering the LED lighting market.

The EC is advocating a strategic approach to building and maintaining a competitive SSL industry. One issue is described as "crossing the valley of death," i.e. translating ideas into marketable products. A three-pillar approach will focus on technological research, product development and demonstration, and advanced manufacturing.

Another key issue is to secure the supply of scarce raw materials, including gallium and indium, as well as various rare-earth materials that are used in phosphor manufacturing. In parallel, technologies should be developed that promote the end-of-life recycling of SSL products. Further requirements include the development of standards; access to intellectual property rights; access to low-cost sources of investment; and learning and training specifically related to SSL, at all levels of the value chain. ◄

SSL in cities

The Green Paper identifies lack of awareness or lack of incentives as reasons why cities are reluctant to use SSL in large-scale outdoor-lighting deployments (see Fig. 1). The high upfront investment cost often clashes with tight city budgets that run on an annual basis, and this creates difficulties even when the overall lifetime cost of SSL is significantly lower. Issues are also caused by the lack of standards with which to develop proper specifications, and the lack of trusted quality-certification schemes.

One option could be to use Green Public Procurement (GPP), an EU-level voluntary scheme whereby public authorities seek to procure goods and services with a reduced environmental impact. Many member states have adopted their own approaches at the national level for supporting "green" procurement.

Financial schemes also exist that could be used by cities to finance feasibility studies for investment in energy-related projects. Examples include European Local Energy Assistance (ELENA) and the European Energy Efficiency Fund (EEE-F). These

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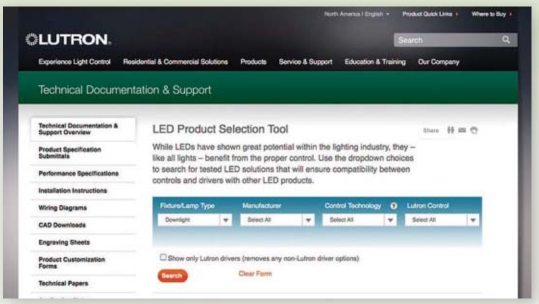

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and other financing mechanisms could be used, says the EC, to plan large-scale SSL deployments. The EC is also suggesting that a dedicated task force should be set up by representatives from cities, the lighting industry and others; this could discuss public-private partnerships, financing schemes, and mechanisms to share information and best practices.

Pilot projects that demonstrate the benefits of SSL and smart-control systems are recognized as being very important. In fact, two or three large-scale demonstration projects, funded by the Competitiveness and Innovation Framework Programme (CIP), are due to be announced soon, following a call that closed in mid 2011 (www.ledsmagazine.com/news/8/2/5).

SSL in buildings

One specific challenge of deploying SSL in private buildings is described by the EC as the "landlord-tenant conflict." This is the mismatch of interests between the building's owner, who pays the upfront cost of the lighting, and the building's user, who usually pays the running costs. The Green Paper highlights the need for financial and other incentives to encourage users to buy and install SSL products. One model could be energy-performance contracting, where a service company makes an investment to install an SSL system, and then receives a return based on the achieved energy savings. The EC also suggests that member states should provide incentives to individual consumers to replace their current lighting with SSL.

In terms of public buildings, GPP can be used by public authorities to support the wider deployment of energy-efficient lighting. Another relevant proposal is for a Directive on Energy Efficiency, which will require public authorities to purchase products (including lighting products) that belong to the highest energy-efficiency class. There will also be obligations for utilities to implement energy-saving measures for end-users, and for the public sector to renovate publicly-owned buildings.

Meanwhile, the Energy Performance of Buildings Directive (EPBD) requires member states to set minimum energy-performance requirements for buildings.

Public consultation

The public consultation invites participants to answer a series of questions (12 in total) included within the Green Paper. These include:

- What can member states do to reinforce the market surveillance of product performance and safety in the area of SSL lighting products?
- Which specific measures would you propose for accelerating SSL uptake?
- Which other actions could be taken by industry to reinforce sustainable SSL manufacturing capacity in Europe?

UV LEDs ramp up the quiet side of the LED market

Relative to visible LEDs, UV LEDs are a quiet market at only $30 million, yet recent breakthroughs in radiant power and intensity have enabled the displacement of mercury-vapor lamps in applications including UV curing and counterfeit detection, reports **LAURA PETERS.**

Below the visible spectrum lies a band of wavelengths called ultraviolet (UV). Ranging from 100 to 400 nm, the radiation can effectively be used to sterilize cosmetics, perform forensic analysis, cure materials (Fig. 1) and disinfect water, among many other applications. Today, as is the case with LEDs in the visible spectrum, UV LEDs are only beginning to replace the established UV sources in a likewise diverse array of markets.

"Compared to the multibillion dollar LED lighting industry, the UV-LED market is a rounding error at around $30 million, but it is growing rapidly," said Mike Lim, director of global industrial and new business for Luminus Devices, based in Billerica, MA.

By far, the UV curing market is enjoying the greatest surge in UV-LED adoption due to the relatively recent breakthrough in flux density of UV-LED chips beyond the 4W/cm^2 mark at the different wavelengths needed to bring UV-LED curing into production facilities. "For the first time, LEDs have reached the power densities that make UV LEDs competitive with existing sources," said Uwe Thomas, general manager of emitter components with LED Engin, a provider of UV and visible LEDs based in Santa Clara, CA.

UV-A, B and C

Curing involves the cross-polymerization of a photosensitive material, which can be an ink (printing), adhesive or coating, and is primarily performed at 395 nm, 385 nm or 365 nm, wavelengths which are part of the UV-A spectrum (315-400 nm). Another important UV-A application is inspection systems based on machine vision. UV-LED flashlights in this range are used to detect fraudulent identification and currency, and offer the benefit of use in well-lit environments, which is difficult using a mercury-vapor lamp.

In the UV-B spectrum (280-315 nm), applications for UV LEDs include curing, medical light therapy, forensic analysis and drug discovery. It has been estimated by market research firm Yole Développement (Lyon, France) that 90% of UV LED applications today are based in the UV-A and UV-B regions (Fig. 4). Yole has stated that it expects the market for UV LEDs to grow by 30% annually from $25 million in 2010 to more than $100 million in 2016. Fig. 5 shows an even more optimistic forecast from the Optoelectronics Industry Development Association, the International Optoelectronics Association and the European Photonics Industry Consortium.

Beyond these applications, UV-B radiation is known to have beneficial health properties including the natural synthesis of vitamin D in humans who are exposed to sunlight. UV-B also accelerates the production of polyphenols in certain leafy vegetables such as red lettuce. Polyphenols are believed to have antioxidant qualities. "Generally these plants are grown in greenhouses today, which intentionally filter out the UV portion of the spectrum in order to maximize plant growth. Interestingly, we have evidence that when those plants are exposed to UV-B LEDs a short time before harvest, their polyphenol content is boosted without compromising plant mass," explained Cary Eskow, global director of advanced LEDs and illumination for Avnet Electronics Marketing in Phoenix, AZ, which distributes UV LEDs. He continued "This is a novel method for increasing the appeal of some foods without using chemicals. Polyphenols also have received attention due to their purported anticarcinogenic, antiproliferative and antimutagenic properties."

In the lower UV-C spectral range (100-280 nm), the primary LED applications are air and water sterilization and a range of analytical tools including those that per-

LAURA PETERS *is a Senior Technical Editor with LEDs Magazine.*

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form spectroscopic and fluorescence measurements. Chemical and biological detectors also work in this spectral range.

UV in the 250-275 nm range sterilizes water, air and surfaces by breaking-up the DNA and RNA of microorganisms and preventing their reproduction. Specifically, 275 nm is believed to be the most effective wavelength for eradicating pathogens such as E-coli in water. In fact, engineers at Sensor Electronic Technology Inc. (SETi), based in Columbia, SC, have determined that 275 nm is the optimum wavelength for water disinfection. SETi has demonstrated disinfection of drinking water in an in-line flow-through system using less than 40 mW of UV power.

FIG. 1. Firefly air-cooled UV-LED-based curing system (source: Phoseon Technology).

Alternatives to mercury arc lamps

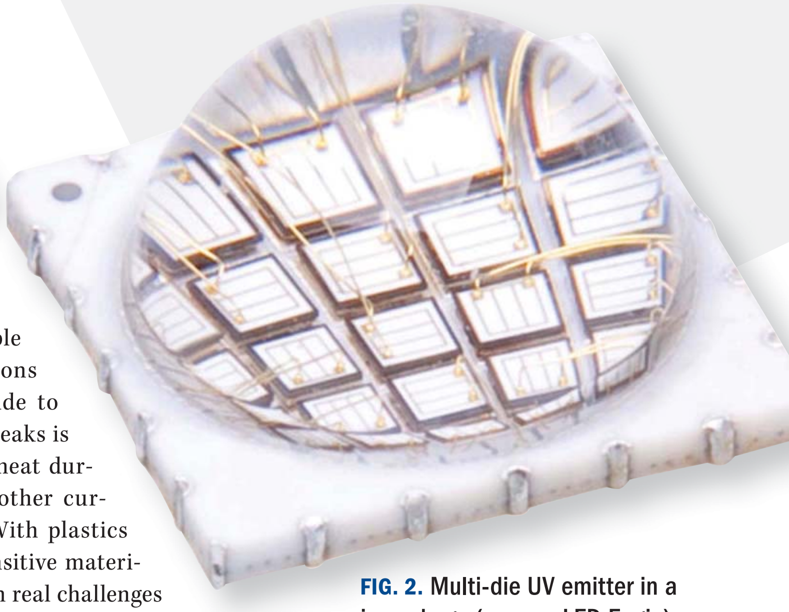
In production curing operations, mercury-vapor lamps are hindered by short lifetime (2000-10,000 hr), slow warm-up and cool-down times, and wide spectral power distribution. "In addition, over 60% of the energy that is applied to a typical mercury-vapor lamp is radiated back out as infrared energy, in other words, heat," said Eskow. He added that the UV output of a mercury vapor lamp drops off rapidly over its operational life because some of its electrode material vaporizes, depositing a film on the inside of the quartz tube which the UV cannot penetrate. As a result, the user cannot easily predict the amount of UV generated at a later time; often this is a critical process parameter.

The mercury lamp has a main peak at 365 nm but several smaller peaks in the visible and infrared regions (Fig. 7). A downside to these extraneous peaks is the generation of heat during printing and other curing operations. "With plastics and other heat-sensitive materials, there have been real challenges in printing because the medium gets distorted from the heat of the mercury lamp," explained Steve Metcalf, CEO and president of Air Motion Systems (AMS), a maker of curing systems based in River Falls, WI. He gave examples that include plastic gift cards or credit cards, which use sheet-fed lithographic printing.

Metcalf added that many people who would not have considered UV curing because of the complexity of standard curing processes – the high voltage, heat of mercury bulbs and environmental issues – will now consider UV-LED curing because it subverts the traditional hassles of the old process.

UV LEDs bring such benefits as knowing precisely what power level is being delivered to the curing medium, as well as other advantages LEDs are known for, such as the ability to pulse-width-modulate the output, stated Eskow.

The transition to UV LEDs also opened the door to more environmentally friendly curing formulations. With the next generation of products that ink, coating and



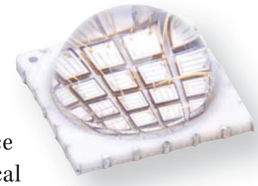


FIG. 2. Multi-die UV emitter in a ceramic package (source: LED Engin).

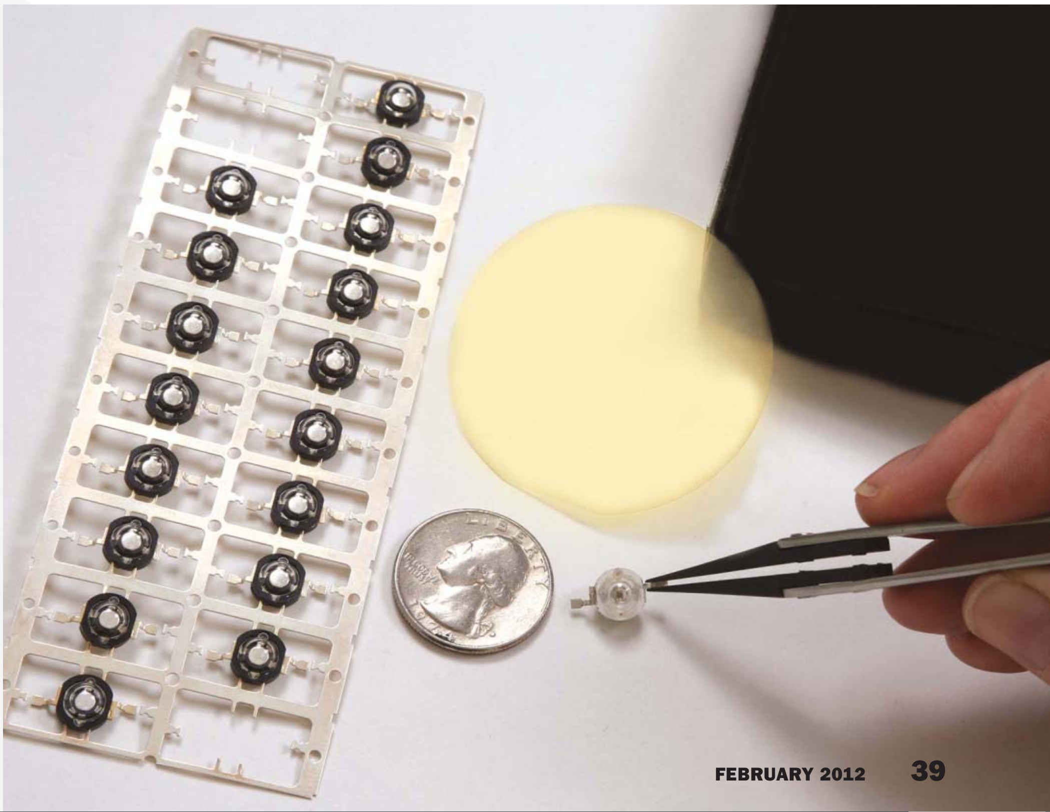


FIG. 3. UV-C LEDs for germicidal applications, from Crystal IS, Inc. The company was recently acquired by Japan-based Asahi Kasei (www.ledsmagazine.com/press/33999).

adhesive companies were developing, they used the opportunity to phase-out volatile organic compounds (VOCs) associated with the solvent-based formulations of past chemistries.

Curing optimization

For the longer-wavelength UV devices, in a similar manner to blue LED fabrication, InGaN-based epilayers are grown on sapphire substrates to produce 385, 395 and 405 nm UV LEDs for curing. One key advantage to higher-wavelength devices is that they can be driven at higher power. “395 nm is really the sweet spot for UV LED curing, because at 405 nm the formulation is sensitive to ambient light, so you want to be just below 400 while being able to drive the LEDs at high power,” said Lim. All the major providers of curing formulations (photoinitiators and resins), have recently brought higher-wavelength inks and coatings to market to fill this need.

In addition to producing more power, the higher-wavelength UV LEDs feature higher wall-plug efficiencies. For instance, at 365 nm, the output power of a UV LED is only 5-8% of the input power. At 385 nm, this efficiency improves, but only to ~15%, making the higher-wavelength chip the better choice.

Curing processes require large, high-power LEDs (multiple die/chip) arranged in a tight matrix in a chip-on-board configuration, close to the emitter window with either an air- or water-cooled internal system to remove heat from the backside of the board. “It doesn’t matter what the UV intensity is at the emitter window, what matters is the intensity at the surface of the media,” said Metcalf. Depending on the equipment and curing application, the media can be 1 to 100 mm from the emitter window, for which AMS has produced special optics. In addition, a metal-cooled PCB is used to sink the heat away from the matrix of LEDs.

Air cooling is also used. For instance, the curing system shown in Fig. 1, which has an emitter window of 150 x 20 mm and flux density of 4W/cm^2, can be used for spot curing inks, coatings or adhesives.

Today, UV-LED curing equipment is often specially designed to fit the application. Metcalf describes large flat-bed banner

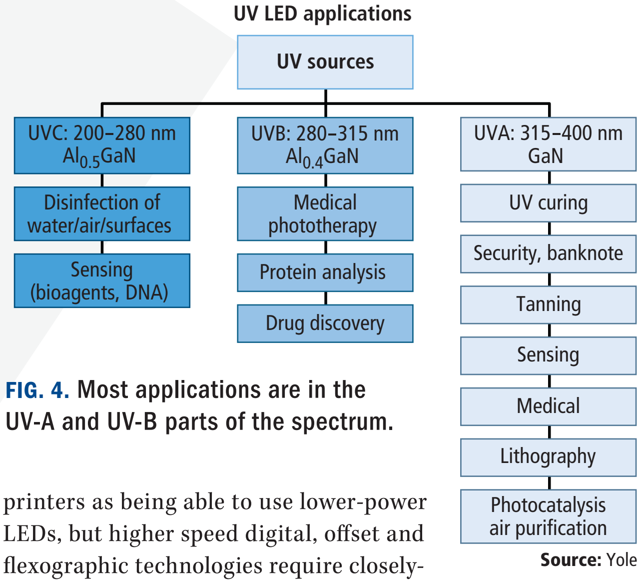


FIG. 4. Most applications are in the UV-A and UV-B parts of the spectrum.

printers as being able to use lower-power LEDs, but higher speed digital, offset and flexographic technologies require closely-spaced banks of high-flux-density LEDs. Even though the radiation is not visible, collimating optics are utilized to deliver the radiation with a uniform power level across the target media. Digital inkjet curing was the first segment to adopt UV LEDs due to the required close distance to the media for the print heads to optimally perform. This was a natural fit for UV-LED lamps as the curing intensity is highest at the emitter window.

Stacy Volk, marketing communications specialist at Phoseon Technology in Hillboro, OR, a maker of UV-LED curing systems, pointed out some of the additional advantages associated with UV-LED curing include a controlled curing intensity, scalable equipment, and the fact that the machines are smaller and compact.

One of the issues the curing industry has faced has been inconsistencies in measurement practice and parameter definitions, for example, defining radiometric intensity. The UV LED Curing Association (www.uvledcuring.org) has been formed recently by curing manufacturers Phoseon Technology, Integration Technology Limited and Lumen Dynamics to “set guidelines and ensure compatibility across the industry,” stated Bill Cortelyou, President and CEO of Phoseon Technology. The association also seeks to help speed development of applications especially suited to UV LEDs, educate researchers, integrators and end users regarding the benefits of UV LEDs, and provide a forum for industry communication and collaboration.

“In our 15 years of experience in LED curing technology, the industry has realized significant breakthroughs that have proven LEDs as a viable alternative that provides substantial benefits,” said Allan Firhoj, President and CEO of Lumen Dynamics based in Ontario, Canada. He added, “The UV LED Curing Association will be instrumental in helping the market gain knowledge and insight about UV LED technology and its numerous commercial benefits.”

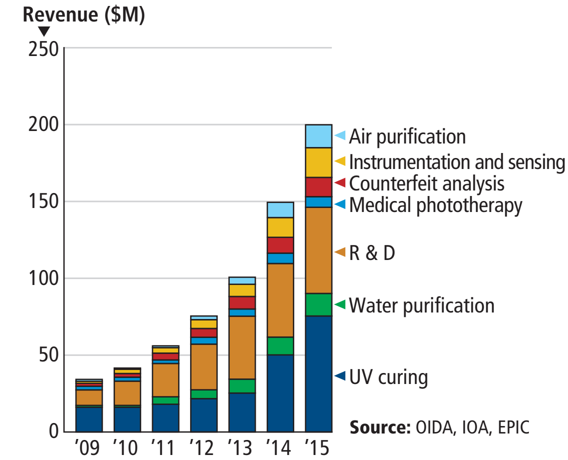


FIG. 5. UV-LED market history and forecast.

A second association, the International LED-UV Association (www.leduv.org), was formed in September 2011 in Japan to organize makers of UV-LED printers, UV-LED manufacturers and ink and coating formulators that are committed to developing sustainable and the environmentally friendly UV-LED printing technologies.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Chip manufacturers

Companies that manufacture UV-LED chips include Crystal IS, based in Green Island, NY (Fig. 3); Dowa Electronic Materials Co. Ltd., based in Tokyo, Japan; Nichia Corp., based in Tokushima, Japan; SemiLEDs, based in Hsinchu, Taiwan; SETi, and Seoul Optodevice Co. Ltd., based in Kyunggi-do, Korea, a wholly-owned subsidiary of Seoul Semiconductor.

UV-LED manufacturers focus on continually improving the efficiency and lifetime of their devices while reducing cost. Seoul Optodevice has a manufacturing partnership agreement with SETi, which manufactures a broad range of UV LEDs and lamps, and performs everything from wafer processing to custom lamp design. The company provides UV emitters in hermetically-sealed metal-glass packages (TO-18, TO-39 and TO-3), with standard products and custom solutions spanning the wavelength range from 240 to 355 nm. Figure 6 shows examples of UV-LED arrays in lamps designed to deliver radiation in the 300-320 nm range for phototherapy applications such as the treatment of skin conditions such as psoriasis or eczema.

Tim Bettles, director of marketing and sales at SETi stated that its manufacturing agreement with Seoul Optodevice is designed to help SETi drive its volumes of UV LEDs and lamps higher while driving down costs. "Our first UV-LED products were launched in 2004 and since then, we have come a long way in both technology development and market adoption. We are now gearing SETi's capacity for high-volume manufacturing to cater to new demands coming from mainstream consumer markets," said Bettles. SETi recently announced the purchase of a new facility, where it plans to manufacture over 100 million UV LEDs per year.

Devin Tang, marketing manager of SemiLEDs stated that the company has a full line of bare dice and surface-mount high power packaged LEDs in the 360-400-nm range. He noted that the company's products are differentiated from others with respect to the chips' copper-alloy substrates, which allow high thermal conductivity (400 W/mK) and silicon substrates in the packages, which reduce cost.

Epigap Optronic, based in Berlin, Germany, the main distributor for Dowa's UV LEDs, stated that Dowa manufactures 265, 280, 310, 325 and 340 nm bare dice or packaged LEDs. Nichia manufactures 365, 375 and 385 nm surface-mount high-power LEDs and low-power lamps. Crystal IS manufactures 260 nm UV LEDs and is the only company to produce LEDs on AlN substrates.

Wafer-processing issues

As was indicated previously, epilayers of InGaN and GaN, grown by MOCVD, are used for higher-wavelength UV LEDs fabricated on sapphire substrates, but at lower wavelengths, epilayers of AlGaN with increasing aluminum content must be used. There are many different compositions involving layers of AlGaN, AlInGaN, AlInN and AlN epilayers, but whatever the composition, it becomes easier to grow AlGaN-based materials on AlN substrates than sapphire at some point, which has encouraged the development of AlN-substrate suppliers such as Hexatech, based in Morrosville, NC. Nonetheless, AlN substrates are only available in small sizes and remain much more expensive than sapphire wafers, thereby limiting this market.

FIG. 6. SETi's UVClean LED arrays deliver very high power deep-UV light at 300-320 nm, the optimum range for phototherapies.

Recently, Theodore Moustakas of Boston University has pioneered the use MBE (molecular beam epitaxy) to grow more efficient (high internal quantum efficiency) UV LED devices using AlGaN-based layers on sapphire substrates. This approach would compete with the various MOCVD techniques used to deposit AlGaN today.

Optics and packaging

Even though UV LED manufacturers have been working hard to improve internal quantum efficiency and optical efficiency, overall efficiency remains below 20%, meaning a great deal of heat must be dissipated from the diode's junction. "To achieve the required flux densities with today's chip technologies, the multi-die emitters need to be driven at the highest current. This is only possible with an LED package capable of handling extreme power densities for the life of the product. A thermally matched

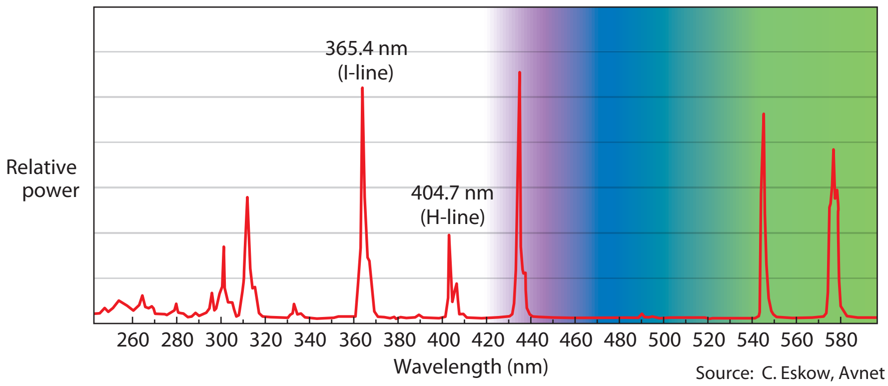

FIG. 7. Spectral output of a mercury-vapor lamp in UV and visible regions.


RELY ON UL

stress-free package and glass lens help eliminate common packaging failure modes associated with UV LEDs," said Thomas. He described LED Engin's patented multi-layer ceramic substrate with extremely low thermal resistance that quickly conducts heat from the die junction (Fig. 2).

While some UV LED arrays are packaged on ceramic substrates, many manufacturers, particularly of single-chip devices, use TO-can type through-hole packages with a glass top that offers high transmission of UV. The replacement of epoxy lenses with flat or dome-shaped glass capable of UV transmission is a relatively new development, and one that has allowed an extension of lifetimes from around 5000 hours up to as high as 30,000 hours. UV accelerates degradation of the epoxy material in a non-linear manner, directly impacting lifetime. The glass lenses provide enhanced durability and improved reliability. Another alternative is to combine a glass lens with silicone encapsulant to accommodate even higher flux density and higher efficiency yet shorter lifetime (15,000-20,000 hr).

The choice of whether to use hermetic sealing in the package is sometimes determined by the materials in the chip. "An aluminum-nitride substrate almost dictates the use of a hermetic package, because the higher the aluminum content, the higher the device's affinity for oxygen, so a hermetic seal will protect the UV device better," explained Frank Gindele, product development manager for Schott Electronic Packaging in Landshut, Germany. The new copper- and glass-based package from Schott offers the advantages of high thermal conductivity and hermeticity.

Dangers of UV

It is important to recognize that some of the same qualities that make UV LEDs very powerful and useful – their low wavelength and high energy – are also the qualities that make them dangerous. The warning labels on UV LEDs and their products are clear but bear noting: UV-LEDs emit invisible ultraviolet radiation when in operation, which may be harmful to eyes or skin, even for brief periods. (For more information on photobiological safety, see our series of articles, Part 3 of which appears on p.63 of this issue.)

Next steps

When asked to identify the key issue that might keep UV users from changing over from mercury-vapor sources to UV LEDs, many industry participants say it comes down to breaking existing industry momentum and, of course, cost. Lim thinks that a rounding out of the wavelength portfolio would go a long way toward adoption. "I think if we can get good 250-nm, 285-nm and 300-nm LEDs, those three wavelengths, then we can pretty much shut the door on mercury arc lamps."


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Use of controls escalates in LED lighting despite lack of standards

Lighting companies are moving forward with adaptive-control technology that can save significant energy especially when combined with inherently-efficient LED sources, explains **MAURY WRIGHT**. However, no standards exist that would allow interoperable use of luminaires, sensors, and controllers from different vendors.

Adaptive lighting control is a necessity going forward given the energy crisis we face globally and the fact that lighting consumes a very large share of the energy used. Efficient solid-state lighting (SSL), using LED sources, is a step in the right direction for slashing energy usage, and controls that eliminate over-lighting can greatly enhance savings. Lighting manufacturers and companies dedicated to sensor and control products support adaptive-control scenarios today, although the networking schemes that link products are largely proprietary. Standards-based networks would enable interoperable products from multiple vendors, but a robust, standardized, lighting-centric network is still a work in progress.

The transition to LED lighting has sparked an increased interest in controls. LEDs are easily dimmable. Moreover dimming SSL delivers energy savings that track the lower light output in a near linear fashion. The efficiency of many LED drivers does drop slightly at less than full load, but the savings remain substantial. The savings that come with dimming aren't as significant with many legacy sources.

Of course commissioning and up-front cost issues remain, regardless of light source type. But controls companies are bringing down cost and making systems easier to use including supporting control applications on popular devices such as smart phones and tablets such as Apple's iPad.

MAURY WRIGHT *is a Senior Technical Editor with LEDs Magazine*.

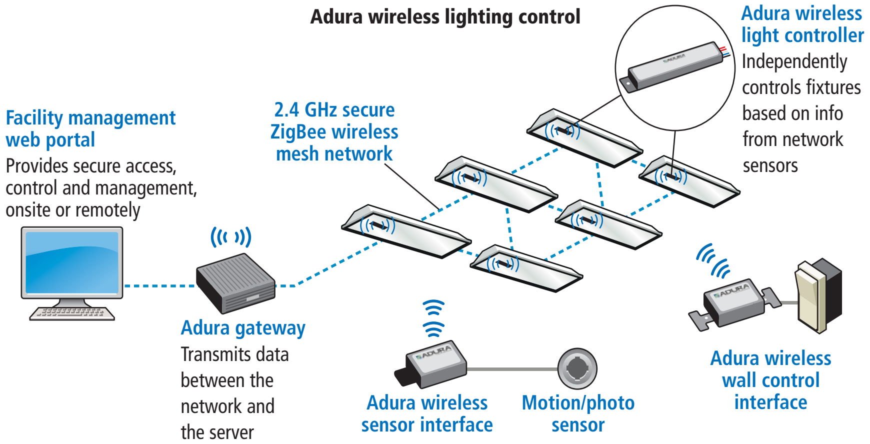

FIG. 1. Adura uses the ZigBee wireless network to connect a gateway with sensor interfaces and light controllers.

The biggest obstacle to broader deployment remains the lack of a full network stack for lighting (see www.ledsmagazine.com/features/7/11/13 for a primer on network technology and the layers that comprise a network stack.) There are wired and wireless networks that could serve in lighting, but in every instance one or more required layers are missing. We will cover those shortcomings through the course of this article.

Control scenarios

Let's examine the current landscape of control schemes by first covering the approach lighting manufacturers are taking to attack the problem. We will then consider the technology that control specialists are offering that can enable systems that mix products from different vendors. Lastly we will look at the prospects for standardized networks.

The major lighting vendors all have some approach to control systems using either wired or wireless interconnects to link lighting and occupancy sensors, switches and dimmers, and light fixtures to a centralized controller. We won't cover the breadth of technologies here, but will consider the approach of Acuity Brands.

Several of Acuity's lighting-centric brands address controls. For example, the Roam brand targets networking of street lights (www.ledsmagazine.com/features/8/2/8). For indoor-lighting applications, the Sensor Switch brand includes a broad array of control products within the nLight family.

NLight relies primarily on a wired network infrastructure using the same Cat-5 cables used for office and home Ethernet networks. Indeed an nLight installation looks like an office network from a topology perspective. A software tool called SensorView resides on a PC and handles commissioning and control. The PC links to the nLight network using an Ethernet connection to one or more nGWY gateways.

Each gateway in turn connects to bridges. For example the nBRG 8 product includes 8 output ports that link to nLight network elements including sensors, wall panels, switches, power-switching modules, and nLight-enabled LED luminaires. Each gateway output can control a multi-element lighting zone with elements daisy-chained via Cat-5 cables.

Network enabled luminaires

Acuity offers the RTLED, ACLED, TLED, and VTLED luminaires through its Lithonia Lighting brand that come with the network connection and a driver equipped for nLight control. You can also add lighting elements to an nLight network that aren't designed for such use. For example the nSP5 D relay and dimming module can both switch AC power to a third-party luminaire and provide 0-10V dimming control.

Sensor Switch has also demonstrated wireless connectivity options. For example, the wireless nPP WIFI module duplicates the functionality of the wired nPP16 relay pack that is a widely used element in nLight networks. The relay packs both switch power to 16A loads and act as a power source for downstream network elements that require a DC power supply.

The nPP WIFI communicates back to the gateway over a standard Wi-Fi network. Sensor Stream value stream manager Michael Clemens said, "It relies on an off-the-shelf 802.11b/g/n router" that ultimately links to the gateway device via Ethernet. Acuity has also mentioned wireless ZigBee links between gateways and bridges in various literature, although no such products are listed on the Sensor Switch website at this time.

Controls specialists

Peruse the websites of other major lighting vendors and you will find similar proprietary networking schemes. Companies that specialize in control technologies, however, have a broader range of network elements, wireless support, and system controllers. And Lutron has perhaps the broadest array of offerings in the segment with products that target light-control in individual residential rooms, whole-house systems, and commercial-building systems. Moreover the lighting controls are part of a larger automation offering that includes control of HVAC systems, motorized window shades, and appliances.

Lutron has evolved a proprietary wireless scheme called Clear Connect over the past 15 years that is a key enabler of its products. For example, in an individual room application, Clear Connect can link a wall-mounted control pad with occupancy and light sensors, dimmer wall switches, plug-in lamp dimmer modules, and other elements. A wireless wall switch that connects to a ceiling-mounted luminaire could switch or dim the load based on local activation of the switch or wireless commands received from the control pad or a handheld remote. The electronic dimmer creates a phase-cut AC signal similar to the output from a triac dimmer and works with any phase-cut-compatible lamp or luminaire.

Whole-house systems build on that functionality via wireless repeaters that extend the range of the network. And Lutron offers dedicated controllers such as the RadioRA 2 and HomeWorks systems that can control multiple rooms or zones. For commercial applications, or perhaps high-end residential, Lutron offers systems capable of controlling more zones and adds a wired interconnect capability called EcoSystem that is

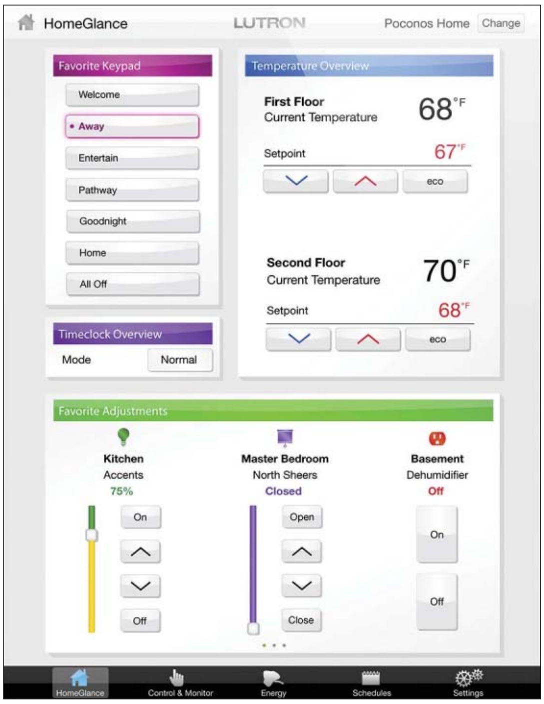

FIG. 2. Lutron iPad lighting-control application.

Controls impact safety, productivity, and experience

While saving energy is the driving force behind lighting controls, there are productivity, safety, and life-enhancement angles as well.

Lutron lead scientist Robert Nachtrieb said that office workers have vastly different preferences for light levels and that given the opportunity many will lower the light level in their work space, reducing energy usage. But Nachtrieb also said there is a corresponding productivity boost. He said, "They are happier, get fewer headaches, and remain more focused on the task."

Nachtrieb also offered a counterintuitive example of increased safety, setting the stage by noting that dim lights aren't typically associated with an increase in safety. He said that in some cases stairway and corridor lights, especially in homes, are turned off to save energy when the only choices are off or on. But given the option of dim lights and energy savings, people would leave lights on at a low level for safety.

Lighting controls can also do more than set levels when a source such as LEDs offers tunable color temperatures. Lance Zheng, Marvell senior manager of technical marketing, envisions lighting controls adding enjoyment to our lives beyond just offering a pleasing ambiance. Zheng suggested that in the future you might have ambient-lighting systems that deliver a lighting track as a compliment to a movie similar to a sound track for audio effects. ◄

an enhanced version of the DALI standard for light control.

Lutron offers only a few luminaires under its Lutron and Ivalo brands. Instead it supports third-party lighting products with the combination of the lamp plug-in modules, wall dimmers, and a broad ballast and driver family that includes the Hi-lume A-Series LED driver family. Lutron has a long list of luminaire partners that offer Hi-lume as a driver option.

The driver offering is broad. Lutron's design development leader Ethan Biery said, "The Hi-lume A-Series has about 3000 different configurations and model numbers." The specifiable options include characteristics such as drive current along with dimming support. In terms of dimming, Lutron offers models compatible with phase control, EcoSystem digital controls, and three-wire controls that have been used with fluorescent ballasts.

Proprietary or standard wireless?

Back to Clear Connect, Lutron has focused its wireless effort on a proprietary system in the 400-MHz frequency band that it believes offers optimal immunity from other signals from cordless phones, Wi-Fi, garage-door openers, and other potential sources of interference. Moreover Clear Connect uses what Lutron describes as a fixed network, meaning that after commissioning there is a predetermined path through the network between any sender and receiver. In contrast, mesh networks such as ZigBee formulate paths dynamically and rely on each network node to retransmit each received packet.

FIG. 3. The graphics-enabled WallPod controller from Sensor Switch (an Acuity Brand).

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FIG. 4. Lutron systems can add control capability to table lamps, recessed spot lights, ceiling fixtures and other lighting elements.

Lutron says that Clear Connect is more reliable and delivers commands more quickly than mesh networks. In reality ZigBee has been widely used in demanding factory-automation applications where latent command delivery can't be tolerated. Moreover the mesh scheme eliminates the need for repeaters or for each sender and receiver to be within wireless range of one another.

But the biggest point of contention over a wireless scheme such as Clear Connect is the proprietary nature. Lutron could decide to license the technology to others. But a network based on an industry standard such as ZigBee should allow any manufacturer to build compatible products.

The operative word in the prior sentence is should. In actuality the ZigBee standard doesn't include the full set of network layers required for interoperable lighting products. ZigBee does ensure reliable delivery of data packets. But it doesn't include the upper network layers that would define lighting-specific protocols and commands. Such layers could still be added on top of ZigBee but today companies using ZigBee for lighting are adding their own proprietary lighting protocols.

Consider Adura Technologies. The company follows a strategy similar to Lutron but uses a ZigBee-based wireless network (Fig.1). The company offers ZigBee-enabled network elements that work with existing third-party sensors and luminaires. For example, an installation would require an Adura Wireless Sensor Interface to be mated with each occupancy or light sensor in an installation. Likewise each luminaire would require an Adura Wireless Light Controller. And the company offers Wireless Wall Control Interfaces that can switch an AC signal and implement phase-control dimming.

Adura also offers a ZigBee gateway that links the lighting network to the office network where a PC can handle commissioning and control. The Adura Lighting Control Software is a web-based platform that supports features such as scheduling. In fact the software can even be used remotely over the Internet. Ultimately the company hopes to have third-parties build luminaires and other network elements with integrated support for its wireless network.

Building an ecosystem

Daintree Networks has also developed a ZigBee-based, lighting-centric network scheme that it calls ControlScope. Unlike Adura, Daintree is not manufacturing any network elements other than a Wireless Area Controller that implements the gateway functionality and enables control and commissioning via the company's ControlScope Manager software. For network elements, Daintree is attempting to

build an ecosystem of third-party partners to support ControlScope.

At present Daintree lists more than a dozen companies as ControlScope Connected partners. The list includes LED-based planar-lighting specialist Lunera Lighting. Partner Finelite is an established player in the commercial-lighting space with luminaires based both on SSL and legacy sources. There are driver manufacturers on the list including eldoLED and manufacturers of sensors and actuators such as SimpleHomeNet. Still it's tough to judge the traction that Daintree has in the market, because the company has yet to announce a major installation.

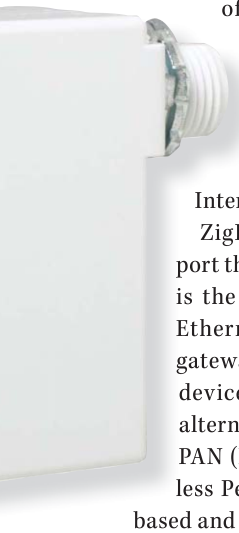
The concept of an ecosystem doesn't apply solely to standards-based networks. Redwood Systems, for instance, is taking that approach with its proprietary lighting system that relies on a wired infrastructure to handle DC power distribution and control signals (www.ledsmagazine.com/news/7/3/7). While Redwood will manufacturer the lighting-control engine and offer management software, it has proactively sought luminaire manufacturers that will build compatible products. Daintree partner Lunera Lighting, for example, is also a Redwood partner.

Lighting companies that want to develop a controls-centric product portfolio don't necessarily require the help of a networking specialist such as Daintree or Adura. Semiconductor manufacturers are developing reference designs and software stacks that can speed the development of products such as network-enabled luminaires. For example at the recent Consumer Electronics Show (CES) in Las Vegas, Marvell announced a ZigBee-based smart lighting platform that utilizes its ICs (www.ledsmagazine.com/news/9/1/7). Marvell will supply reference software to its customers for free hoping to accelerate the controls marketplace.

FIG. 5. Sensor Switch nLight Wi-Fi module.

Standards outlook

Looking forward, the standards forecast is unclear. Ideally the industry will develop a standard that would allow interoperable products just as consumers can buy interoperable computer-network elements. The ZigBee Alliance has developed the ZigBee Building Automation layer that addresses controls for HVAC and other systems. And the organization is working on a lighting-centric upper-layer protocol called ZigBee Light Link.



But some industry participants aren't sold on ZigBee as the basis for a lighting network, or in a larger sense, a network of smart devices that pervade our lives. Sometimes referred to as a network of things, the concept is that virtually every electronic device will be linked on the Internet going forward.

ZigBee doesn't inherently support the Internet Protocol (IP) that is the basis for the Internet and Ethernet networks. Of course a gateway can link ZigBee-enabled devices to the Internet. But an alternative protocol called 6LoWPAN (IPv6 over Low power Wireless Personal Area Network) is IP based and is gaining momentum.

Smart objects

At a recent IPSO (Internet Protocol for Smart Objects) Alliance event called the Internet of Things, NXP Semiconductors demonstrated a 6LoWPAN-based lighting network. The company has developed a 6LoWPAN protocol stack called JenNet-IP that works with some of its microcontrollers. The demonstration featured Android devices and iPads controlling smart lights via the Internet.

The 6LoWPAN protocol can operate over the same lower network layers defined in the IEEE 802.15.4 standard that also underlies ZigBee. But even the 802.15.4 physical and media-access-control layers aren't a sure bet for a future universally-accepted lighting network.

Google, for instance, wants to insert itself deeper into our lives and Android provides a potential avenue. Last May at the Android Developers Conference, Google announced an initiative called Android @ Home and demonstrated a prototype of a smart LED-based retrofit lamp developed by Lighting Science Group (www.ledsmagazine.com/news/8/5/9).

Back in May we speculated that Android @ Home would be based on 802.15.4. Google has been pretty quiet on the subject. But recent rumors point to the company developing a simpler alternative to 802.15.4 that would be cheaper to implement enabling lower-cost smart objects such as controllable LED lamps. Google is expected to use 6LoWPAN in Android @ Home.

While Google isn't targeting commercial lighting, it could impact that segment were it to deliver an open network that could be used by other companies. Meanwhile the quest for a lighting-centric network continues while proprietary deployments also escalate. Indeed there is little reason not to implement smart lighting today, especially in the commercial space. Such projects are paid back rapidly via reduced energy costs. And today's proprietary networks will be compatible via gateways with future standardized technologies.

LED lighting at Louvre symbolizes Toshiba's move into Europe

A ceremony has been held to mark the first phase of a project to install LED exterior lighting at one of Europe's great art museums, writes **TIM WHITAKER**.

Toshiba Corporation recently completed the first stage of a project to replace the external lighting at the Louvre Museum in Paris, France, with LED lighting. The first stage involved the lighting inside the iconic central Pyramid, as well as the three surrounding pyramidions (small pyramids) and a section of the facade of the Colbert pavilion, part of the main museum building. The lighting was switched on during a ceremony on December 6, 2011, by Norio Sasaki, president and CEO of Toshiba Corporation, and Henri Loyrette, director of the Louvre Museum.

Essentially this is an architectural lighting project: there are no plans yet in place to install LED lighting in the galleries, although the Mona Lisa painting is illuminated with a standalone, purpose-built LED light source (ledsmagazine.com/news/2/5/5). However, both the project and the launch ceremony make a clear statement about Toshiba's intentions within the European lighting market. Toshiba made a high-profile debut in Europe at Light+Building in April 2010, and all the company's lighting products in Europe are LED-based. François Séguineau, VP Europe with Toshiba Lighting Systems, said that Toshiba is now a "top-3 supplier of LED lamps in Europe."

The partnership between Toshiba and the Louvre Museum, which will run until 2023, was first announced in July 2010 (www.ledsmagazine.com/news/7/7/1). In the next phases of the project the remaining facades of the Napoleon Court will be completed in the first half of 2012, and the courtyard will follow in 2013.

Overall, Toshiba will provide a total of 3200 LED light fittings to replace 4500 xenon light fittings. The LED retrofit will cut annual power consumption for the exterior lighting by 73%, from 392,000W to 105,000W. Six different fixture types, including 15-LED linear fixtures for the Pyramid (Fig. 2), and exterior floodlights (Fig. 3), were purpose-designed for the Louvre installation. The lighting had to meet various technical specifications, but also meet certain subjective and aesthetic requirements. Takayoshi Moriyama, a Toshiba lighting specialist, explained how the project differed from a typical one. "We would typically use tools such as specification drawings which would be finalized by the sales manager after consultation with the client," he said. "We would then make a prototype of the fixture, re-check its optical and electrical performance and – barring any problems – progress from product development to product certification in a short time frame, with delivery date as the top priority." Although Toshiba's prototypes and specifications were approved by the Louvre's technical directorate, they were then subject to a second, detailed screening by the museum Director and the Historical Monuments Committee of Paris. Moriyama said there was considerable debate about the size, shape and color temperature of the fixtures (2700K was eventually settled on). "We had to harmo-

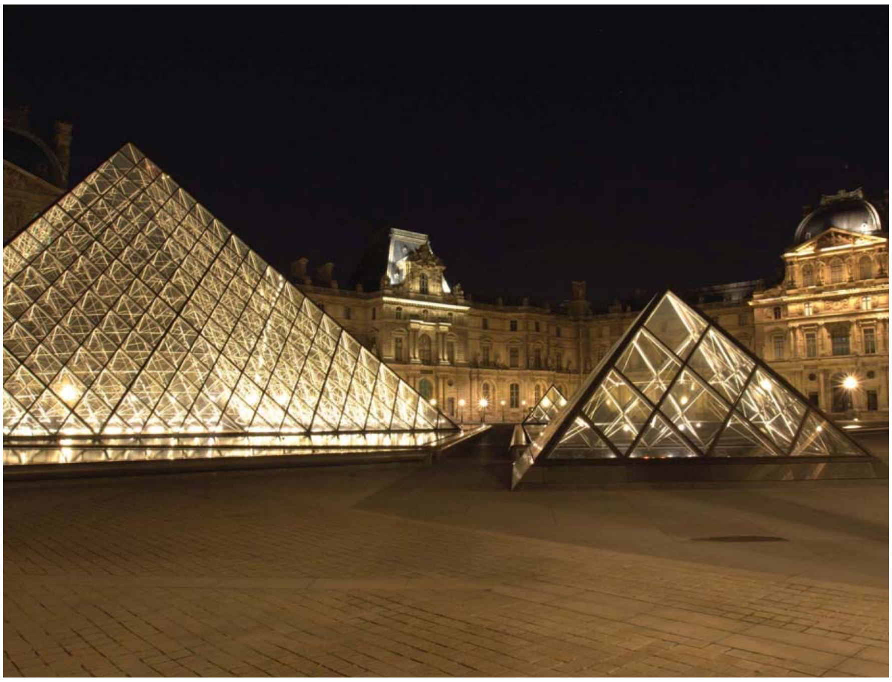


FIG. 1. Toshiba has installed LED lighting in the Louvre's Pyramid, the pyramidions, and the façade of the palace building.

nize the fixtures with the building as part of the scenery," he said.

Vision and branding

In a lighting seminar accompanying the switch-on ceremony, Masami Fukuda, president of Toshiba Lighting & Technology Corp, said that the company's lighting revenue for the year ended March 31, 2011, was €5 billion, or 9% of total sales. He stated that Toshiba's vision statement for the lighting business is "Lighting the way to warmth and harmony with people and the environment." LED technology is seen as combining "people's value creation" – which includes comfort, culture and emotion – with "environmental value creation," which includes higher efficiency and life-cycle cost reduction compared with competing technologies.

As well as Toshiba's technological capabilities and its ability to create synergy with smart energy-management systems, Fukuda pointed to the importance of leveraging Toshiba's brand, which he described as a "trusted brand in consumer electronics with its quality." Branding and reputation are clearly important attributes for companies like Toshiba, along with its peers such as LG, Panasonic, Samsung and Sharp, who have all introduced lighting products into the European market. These are not traditionally recognized as lighting companies in Europe, although the Japanese companies are strong in their domestic lighting market.

As LED lamps become more prevalent, consumers will need to adjust to paying higher prices for lamps, with the promise of energy savings and longer life. They may also need to start to think of lighting in terms of being more like a consumer-electronics product, and less like a very-low-cost consumable item. As this shift occurs, the reassurance of a brand with a reputation for quality could prove to be a decisive factor when the consumer makes an investment in LEDs.

FIG. 2. Linear LED fixtures installed in the interior of the Pyramid.

Vertical integration

Meanwhile, Séguineau claimed that, within two years, Toshiba has become "a key European player in the LED market."

The company's strategy has been to focus first on commercial lighting, second on street lighting, and third on residential lighting – and as stated above, all its products for the European market are LED based. Toshiba is using a 100% indirect-sales model, using wholesalers and energy-saving companies for business-to-business sales; retailers for business-to-consumer sales; and selling LED light-engines to lighting manufacturers. In this last case, Séguineau said that Toshiba is looking to achieve "Toshiba inside" recognition in the branded products of other companies.

FIG. 3. LED floodlight module for the Court Napoleon facade.

Masao Segawa, chief technology executive of Toshiba Lighting, described a new 90-mm-diameter light engine with a new socket (GH76P) that has an output of either 1100 or 1600 lm, and a beam angle of either 45° or 85°. He also described a new version of Toshiba's A-shape E26 LED lamp that has a light distribution of 260°, compared with only 120° for the previous version. The LEDs are still on a horizontal plane, but special optics are used and the light is reflected from the inside of the lamp cover in order to provide the desired light distribution. The 10.6W lamp has an output of 1000 lm.

Toshiba is a supplier of many types of electronic components, including laser diodes, and is now increasing its internal production capacity for LED chips. Masami Fukuda told *LEDs Magazine* that "some of Toshiba's LED lamps already use the company's own LEDs," and that the intention is to become more vertically integrated in the future.

TIR optics enhance the illuminance on target for directional LED modules

Secondary optics using total internal reflection perform better than reflector-based optics for constructing directional LED-based modules, but only if the light-distribution pattern is correctly evaulated, write **WU JIANG** and **KEVIN SCHNEIDER**.

Directional LED modules and lamps can be designed in different ways to provide the desired result of placing the light where it is required for a specific application, while minimizing glare and background light. This article compares two alternate approaches, one based on a compact emitter in combination with a secondary lens using total internal reflection (TIR) optics, and the other based on a chip-on-board array in combination with a reflector.

However, as this article also emphasizes, comparisons of LED modules and lamps by power consumption or luminous efficacy – or even the nominal beam angle – may give a completely inaccurate impression of the performance of these light sources.

FIG. 1. TIR lenses and compact, high-lumen-density emitters from LED Engin. The company manufactures four compact emitter packages: 1-die up to 5W, 4-die up to 15W, 12-die up to 40W, and 24-die up to 80W.

Making comparisons

It is easy to compare the performance of incandescent lamps; products conform to common, long-established physical formats and they emit light in very similar ways. For a given AC grid voltage, the primary way of comparing incandescent lamps is by their power rating in watts, and consumers have a clear idea how much more light is likely to come from a 100W lamp than from its 60W counterpart.

The emergence of LED lamps has made things a bit more complicated, not least because the industry has tried to explain the performance of LED lighting in incandescent terms. Specifications usually include the power consumed in watts and how that equates to an equivalent incandescent lamp. The luminous efficacy value (lm/W) is also quoted.

However, LED lamps have a more complex construction than incandescent ones. Many factors – such as the type of emitter, the substrate upon which the emitter is mounted, the driver electronics, the optical focusing mechanism, and the housing – all contribute to differences in performance.

Using luminous efficacy to compare LED lamps can be totally misleading, particularly when it comes to directional lighting. The two directional LED modules compared below have similar specifications, including efficacy, but more detailed evaluation reveals quite staggering differences in performance in real-world applications.

The need to focus

High-power LED emitters are ever-improving light sources for a broad range of lighting applications. However, for the vast majority of applications, such as interior spot- and down-lighting, roadway lighting, architectural lighting and stage lighting, the emitters alone cannot deliver enough light intensity to a target. This is because an LED light source emits a Lambertian light distribution whereby the apparent brightness to an observer is the same, regardless of that observer's position. Light is therefore spread far too widely.

In order to direct light onto a target, it

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is necessary to use secondary optics, which collimate the light into a controlled beam illuminating the targeted area. Collimated light rays propagate in parallel, although perfect collimation is not possible due to diffraction and the finite size of the emitter. However, the smaller the light source, the more effective the collimating optics can be. Besides collimating light, secondary optics can also be designed to improve color uniformity and light distribution within the target area.

To describe the ability of secondary optics to collimate a beam, we often refer to viewing angle or full width at half maximum (FWHM); this is the angular width of the beam whose intensity at the edge is half the maximum intensity in the center of the beam. This angle is a useful way to classify optics, but it doesn't always explain discrepancies between different optical platforms. In practice, depending on the optical design, optics with identical viewing angles can differ quite a lot in the intensity and quality of the beam.

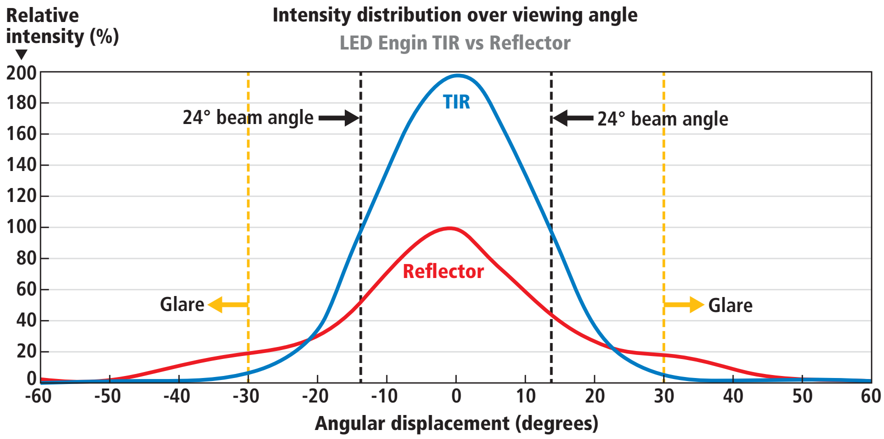

FIG. 2. The TIR lens produces twice the center-beam lux with negligible glare.

Reflectors and lenses

Many lighting applications – in particular high-bay lighting, street lighting, and stage lighting – demand high illumance (measured in lux) at a distance, and that means both a high-power emitter and a highly collimated beam. In an industry with such high standards, it is essential that each emitter be properly matched with appropriate secondary optics.

Often, the physical size of the emitter limits the optical options. This is particularly true of certain chip-on-board (COB) or array emitters; they emit from such a large area that the only optical solution is to surround the emitter with a reflective surface.

Reflectors are common with omnidirectional lights such as incandescents, but in LED designs they carry a key disadvantage: a majority of light rays originating from the center of the emitter pass out of the system without ever touching the reflector. This means that even in a narrow-flood reflective system, where the view angle is in the 20-25° range, a significant portion of the light strays wide of the target. And it isn't simply lost; worse, it is very visible as glare and background light, causing distraction and discomfort at the expense of center-beam lux.

Contrast this with the optical opportunities for a compact, very high lumen-density emitter. These emitters are powerful enough to provide the necessary luminous intensity (measured in lumens) and small enough to be enveloped with a TIR lens to guide virtually all of the radiated light toward the target. An inexpensive, efficient, well-designed lens in a low-profile form factor is only possible with such very bright, very compact emitters.

The lenses in Fig. 1 produce viewing angles from 8° to 45° when used with compact emitter packages (all products shown are from LED Engin). The secondary optics not only direct light to the target but provide high optical efficiency and color uniformity while maintaining compact form factors.

	TIR lens with SMD emitter	Reflector with COB array
Number of die	12 die (1 x 1 mm)	24 die (1.5 x 1.5 mm)
Luminous intensity (lm), input power (W), efficacy (lm/W)	985 lm, 17.79W 55.4 lm/W	969 lm, 17.84W 54.3 lm/W
Center-beam illuminance (lux) at 1m	6020	3005
Lux efficacy (lux/W) at 1m	338	168
Glare (percentage of radiated energy outside of 60° cone)	6%	28%

TABLE 1. Comparison of LED-based modules with similar headline specifications (lm, W, lm/W) and the same sized optics (45-mm diameter × 25-mm height). The TIR lens delivers twice as much light to the target and 80% less visual glare.

TIR lenses versus reflectors

In order to compare the performance of TIR- and reflector-based approaches, two LED modules were evaluated. One module used an LED Engin compact LZC emitter with a 24° TIR lens, while the other used a reflector-based module containing a COB array. In both cases, the optics had the same dimensions (45-mm diameter, 25-mm height). Both modules were designed to have a FWHM of 24° and their specifications were matched as closely as possible, particularly the luminous intensity (lm) and efficacy (lm/W).

Table 1 illustrates three key differences in performance between these modules. For example, the TIR lens system delivered twice the central lux of the reflector module, with 2× the "lux efficacy" measured in lux/watt.

Fig. 2 shows the measured intensity distribution over viewing angle. We can immediately see that FWHM viewing angle (in this case 24°) doesn't tell the whole story. The TIR lens design produces a smooth, well-controlled slope up to the peak intensity, while the reflector's intensity distribution flattens out in the wide-angle glare zone.

This is perhaps more visually evident in the 3D graph in Fig. 3, where the profile of the TIR-based module shows a smooth gradient toward the center beam, but the reflector solution shows a more "spiky" center beam with a significant portion of the reflector's energy coming from outside the peak.

In fact, 28% of the radiated energy from the reflector design falls outside of a 60° cone, contributing to glare, while for the TIR design this is only 6%.

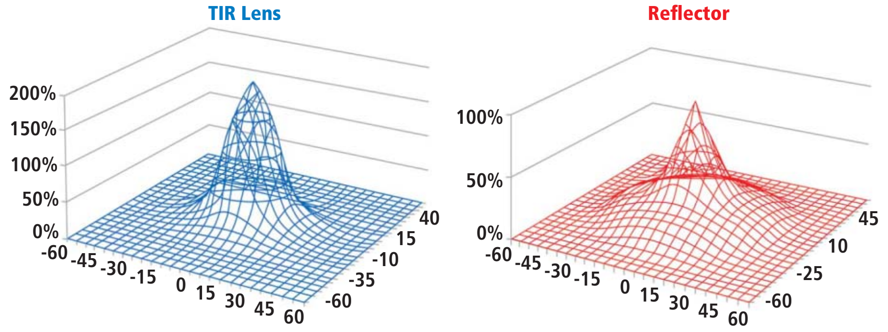

FIG. 3. A 3D beam profile clearly shows the smooth illumination profile and central illuminance (lux) performance of the TIR module compared to the lower lux and higher glare from the reflector module.

Summary

In real-world applications, comparisons of LED modules and lamps by either power consumption or luminous efficacy may give a completely inaccurate impression of the performance of these light sources.

What's needed is a new way of defining luminous performance that takes into account the percentage of lux-on-target that's delivered, not the total lumens produced by the module. True "lux efficacy" could perhaps be adopted to describe the useful lumens produced by an LED module i.e. the light which illuminates the target area.

Other factors such as color uniformity and light distribution still have to be considered, but lux efficacy would be a better measure than anything currently available. The comparison between modules with reflector designs and TIR lenses clearly demonstrates the need for such a measure.

LED-based products must meet photobiological safety standards: part 3

To conclude our series of articles on LED photobiological safety, **LESLIE LYONS** puts IEC62471 to work in consideration of the hazards posed by today's LEDs and LED-based products.

Parts one and two of this series on LED photobiological safety focused on the potential hazards to the human body posed by exposure to optical radiation; the development of standards and their application; and the fine details of source evaluation (www.ledsmagazine.com/features/8/11/15).

This third part of the series focuses on the use of the IEC62471 standard to evaluate LED-based products. IEC62471 may be used to evaluate personal exposure to optical radiation, within, for example, the scope of the EU Artificial Optical Radiation Directive. However, its principal use is in providing a framework for evaluating the photobiological safety of finished products intended for sale on the market. The responsibility for ensuring that such an evaluation is performed resides with the manufacturer of the finished product, who, in many cases, is wont to reduce this burden.

It is clearly not possible to measure every LED in use, and indeed in many cases there is no need to do so. For example, the low visual response elicited from low-power white or colored LEDs leads one to reason that no photochemical safety concerns exist. However, as one considers LEDs of increasing optical power, the point at which one can no longer make such assumptions may not be obvious.

When are measurements required?

In the first instance, IEC62471 recommends that detailed measurements are not required for sources having a luminance less than 10^4cd/m^2. This level is considered as one visually comfortable to view. The guidance is based on the expectation that, at this level, exposure limits will not be exceeded. However, it only applies to white or broadband sources emitting over the visible region.

Luminance does not fully take into account the emission of colored LEDs, nor does it take into account UV or IR emission. The luminance of a UV source may be below this level, yet one cannot use this information to base a conclusion on a potential UV hazard. In practice, this threshold luminance is particularly low, and is exceeded by many, even low-power, white LEDs.

Where the luminance of a white-light source exceeds this level, and for all other sources, one should proceed with the evaluation of photobiological safety, at the appropriate distance – 500 lx or 200 mm – depending on the intended application of the finished product.

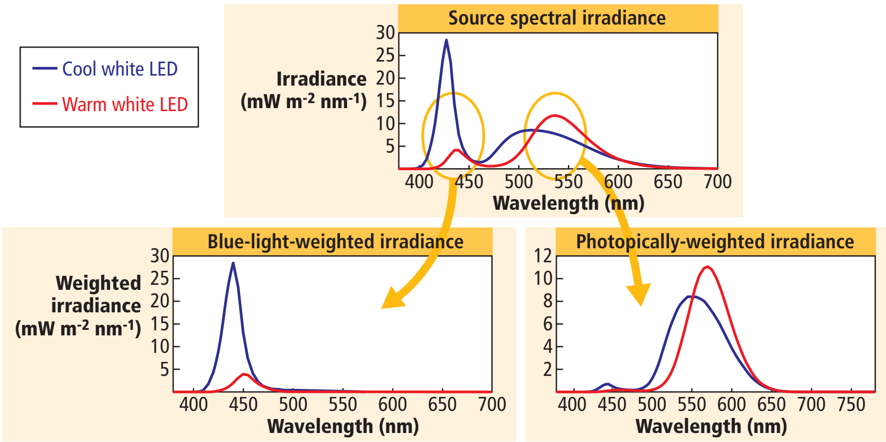

FIG. 1. Blue-light-weighted versus photopically-weighted irradiance for cool- and warm-white phosphor-converted LEDs. While the photopic integrals may be similar, the blue-light integrals differ significantly.

GLS products

General lighting service (GLS) sources are defined as white-light sources used to illuminate spaces. Within the context of LEDs, consideration is made of two technologies: phosphor-converted (PC) and color-mixed LEDs. Due to the narrow-band emission of LED chips, and the limited emission range of LED phosphors, one can restrict consideration to the visible region: no risks are posed in the UV or the IR.

Practically, the sole hazard in consideration is the blue-light retinal hazard, which dominates over the retinal thermal hazard for exposure times greater than ten seconds. It follows that it is the blue LED of both PC and color-mixed LEDs which gives the main cause for concern.

Consideration of the blue-light hazard of GLS sources is most conveniently demonstrated in evaluation of radiance through a measurement of irradiance, comparing the blue-light-weighted irradiance with the

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illuminance of the source (Fig. 1).

For a given illuminance, the higher the emission in the region of the blue-light hazard function, the greater the blue-light hazard posed. An increasingly prominent blue-emission peak lends a source a blue appearance, characterized by an increasing correlated color temperature (CCT). It can be demonstrated that at 500 lx, only LEDs having very high CCT (greater than approximately 10,000K) exceed the limits of the blue-light exempt risk group (RG), and that no sources will exceed blue-light RG1 (risk groups are discussed in Part 1). Since such high-color-temperature sources are seldom used in SSL applications, one can conclude that few GLS sources will pose any hazards at the 500-lx evaluation distance.

On the subject of GLS, two other points should be made. Firstly, with regard to certain sources, such as desk lamps and household spot lights (for which the determined 500 lx distance may be significantly greater than a likely exposure distance), the lack of clarity in the definition of GLS in IEC62471 has led to disagreement between laboratories of whether GLS or non-GLS measurement conditions should apply.

Secondly, and counter-intuitively, consider two GLS products, differing only in number of component LEDs or drive current. If the spectral output of both sources is the same, then the IEC62471 hazard evaluation is also the same, albeit performed at different 500-lx distances. Such a result may make sense where the two sources are used in distinct applications. However, in the not-uncommon case that they are marketed as alternatives for the same application, this further demonstrates that the evaluation at 500 lx is not a satisfactory point of reference.

Non-GLS products

The non-GLS category takes into account all types of LED, through the spectrum from the UV to the IR, including white LEDs used in non-GLS applications. Depending on the application, the optical output of such LEDs can vary significantly from very low-level indication to high-power LEDs used for example in industrial and signaling applications.

The analysis here is rather more detailed than is the case for GLS sources: at the close proximity of 200 mm, elevated risk-group classifications may indeed result, and there may be cause to consider multiple hazards for a single product. Table 1 provides an overview of the maximum reported RG of LED-based non-GLS products for each hazard considered by IEC62471. This excludes the thermal skin hazard, not part of the classification system.

Hazard	Wavelength range (nm)	Max. reported risk group
Actinic UV	200-400	RG3
Near UV	315-400	RG3
Blue light	300-700	RG2
Retinal thermal	380-1400	Exempt/ RG1
IR eye	780-3000	RG3

TABLE 1. Maximum reported risk group (RG) of LED-based non-GLS sources.

In terms of the irradiance-based hazards, RG3 is certainly attainable, if not from a single LED, then by an array of LEDs. On the other hand, in the case of radiance-based hazards, since the measurement field-of-view (FOV) generally encompasses one, or a small number of, component LEDs, the maximum classification depends less on the collective effect of multiple LEDs in an array than on the output of individual LEDs.

While current blue-LED technology exceeds blue-light hazard RG1 by up to an order of magnitude, the RG2 limit is a further two orders of magnitude away. Furthermore, the often-cited fact that even the sun is an RG2 source would suggest that blue-light RG3 sources do not exist. Also, LED radiance is not sufficient to cause thermal damage to the retina; such damage can generally only be elicited by directly viewing certain lasers or arc lamps.

Analysis based on LED maker's data

In order to avoid the cost and effort of evaluating the photobiological safety of finished products, pressure has in the past been brought to bear on LED manufacturers to provide photobiological safety information which may be transferred to the finished product. It is clear that an IEC62471 evaluation of a bare LED is not directly transferable to a finished product, which may include multiple emitters and beam-shaping optics, so another strategy should be employed.

The irradiance of the finished product cannot in any way be predicted. However, in the case of radiance-based hazards, a measurement of the true radiance, coupled with the law of conservation of radiance, may be used to determine the maximum possible radiance of any finished product using a given LED.

IEC TR 62471-2 introduces this principle for the evaluation of the blue-light hazard (the dominant concern for retinal injury) through a measurement of true radiance of

IEC62471 analysis				
Risk group	Angle of acceptance (mrad)	Measured ($W m^{-2} sr^{-1}$)	EL ($W m^{-2} sr^{-1}$)	IEC62471 analysis
Exempt	100	1.9×10^3	100	FAIL
RG1	11	9.1×10^3	1×10^4	**PASS**
RG2	1.7	1.2×10^4	4×10^6	-

Worst-case analysis Measured blue-light radiance (1.7 mrad) = 1.5×10^4 $W m^{-2} sr^{-1}$		
Risk group	EL ($W m^{-2} sr^{-1}$)	Worst-case analysis
Exempt	100	FAIL
RG1	1×10^4	FAIL
RG2	1×10^6	**PASS**

TABLE 2. Comparison of IEC62471 and worst-case analysis for blue-light hazard. (EL = exposure limits.)

the component LED at 200-mm distance and 1.7-mrad FOV. The resulting value is adopted as the blue-light radiance of the final product, to be compared with the exposure limit values of each risk group in turn. It is important to note that care should be taken to ensure that the data provided by the manufacturer provides a correct analysis for the operating conditions of the finished product.

This procedure leads in many cases to an over-estimation of the hazard, since account is not taken of physiological radiance. This is demonstrated in Table 2, where a comparison is made between an IEC62471 analysis and a worst-case analysis of a particular product. In the former case, each RG is considered in turn, with measurements being performed in the correct FOV and compared with the RG exposure limit (resulting in an RG1 classification). In the latter case the worst-case radiance is assumed and compared with the limits of each risk group in turn (resulting in an RG2 classification).

A similar result is obtained in many instances, especially when considering high-power LEDs used in SSL applications. According to IEC TR 62471-2, blue-light RG2 requires the use of a warning label. This means that the lighting industry has been faced with the decision of either determining how to implement the recommendation of labeling, or not accepting such worst-case analysis evaluation, which clearly has no bearing on the true hazard posed by the source in the intended application. This procedure has generally been discontinued while awaiting a more acceptable solution, as will be seen below.

Analysis based on LED data-sheet values

Where no photobiological safety-evaluation information is available from an LED manufacturer, some have sought to make estimations based on data-sheet values, which typically report beam-emission angle and either total flux or intensity in photometric (lumen, candela) or radiometric (W, W/sr) quantities, depending on whether the LED emission wavelength is within or without the visible region.

Given the emission angle and the evaluation distance, the area illuminated by the LED may be determined and either total flux or intensity used to make an estimate of irradiance. To estimate physiological radiance, it is required to know both the intensity and the FOV area corresponding to the RG considered. Where intensity is not directly reported in the datasheet, it may be calculated from the total flux and beam-emission angle. In the case of white or colored LEDs, where photometric data is often provided, a conversion factor (lm/W) must be determined to convert to radiometric units.

In the case of hazards requiring the application of a hazard-weighting function, estimation without taking such into account represents an over-estimation. This errs on the correct side of caution, as befitting such an analysis. Again, care should be taken to ensure that the data pro-

vided by the manufacturer provides a correct analysis for the operating conditions of the finished product.

Should such a calculation indicate the existence of a classification that is higher than exempt, correct measurements are recommended. It need not be stated that the uncertainty associated with such estimations are necessarily high.

Hazard distance

IEC TR 62471-2 also introduces the concept of mapping out the photobiological hazards associated with a source by determining hazard distance information to cover all potential applications. This procedure consists of the evaluation of a source at the minimum accessible distance, no less than 200 mm for the retinal hazards, and the determination (should any hazard be in excess of the exempt RG) of the distance from the source at which exposure is decreased to the required level for each remaining RG.

For irradiance-based hazards, this procedure is relatively straightforward, although one may be hampered by the requirement of measurement in a 1.4-radian FOV for all but the thermal skin hazard. The inverse-square irradiance law may be used with caution, but such calculations should not be necessary since irradiance can readily be measured at other distances by a number of techniques, such as the use of a lux-meter to seek an illuminance corresponding to the given level of irradiance sought.

Radiance-based hazards are more difficult to handle since measurements should be made in a specific FOV. Where the source subtends an angle less than the field of view, the hazard distance can be predicted since it will reduce with the square of the measurement distance, as the area of dark covered by the FOV increases.

Where a single emitter subtends an angle greater than the FOV, as a first approximation, physiological radiance will be constant until the distance at which the source subtends an angle less than the FOV. In the case of arrays, the physiological radiance may not decrease sufficiently before more LEDs fall into the FOV in which case, as a first approximation, physiological radiance will be constant until the distance at which the entire array subtends an angle less than the FOV (Fig. 2).

Hazard distance of LED luminaires

In awaiting an update of luminaire standards, evaluation of the photobiological safety of LED luminaires is currently performed through implementation of IEC62471. This situation has provided little satisfaction due to issues with the evaluation at 500-lx distance and the implementation of worst-case analysis to permit the transfer of LED manufacturer's data. IEC committee SC34A is currently working on this issue, in considering the implementation of a restricted version of the hazard-distance analysis relative to the sole concern of white LEDs in GLS applications, namely the retinal blue-light hazard.

Based upon the assumption that light sources classified as exempt or RG1 for blue-light hazard are suitable for GLS applications, both component LEDs and finished products should, in the first instance, be evaluated at 200 mm in an 11-mrad FOV, with the spectral range extended to 300-780 nm to cover both blue light and photopic regions. This measurement serves as both an analysis of blue light RG1, and as a worst-case analysis, assuming that true radiance is measured.

Where the resulting blue-light radiance is below the RG1 exposure limit, the component LED or finished product may be considered exempt/RG1 in all conditions. Where the RG1 exposure limit is exceeded, the RG1 hazard distance should be determined through the evaluation of radiance as an irradiance measurement, with respect to a corresponding RG1 exposure limit expressed in blue-light-weighted irradiance. Given the ratio of luminance to blue-light radiance, the illuminance level at which the RG1 blue-light irradiance should be obtained is determined.

In the case of finished products, the distance at which this illuminance is obtained should be reported by using a luxmeter: at distances closer to the source than this distance, RG2 applies, elsewhere RG1/exempt applies. In the case of component LEDs, the illuminance value is simply reported in the data sheet such that the finished-product manufacturer can apply the aforementioned procedure to determine the RG1 distance for the particular product under consideration. This procedure is alas not quite as simple as it looks since the measurement should be performed in an 11-mrad FOV: not doing so will over-estimate the RG1 distance.

How luminaire standards will in future implement the RG1 hazard distance is still a work in progress, but it is clear that one can tolerate greater RG1 distances for ceiling-mounted applications compared for example to portable luminaires.

IECEE CB scheme & product marks

It is solely in Europe that IEC62471 has been implemented within a legal framework. However, IEC62471 has worldwide renown, through the implementation of the IECEE CB scheme and a wide range of product marks.

The IECEE CB scheme was set up to facilitate international trade in electrical equipment and is based on IEC product standards and a principle of mutual recognition of test results. Put simply, a manufacturer in country A, wishing to market his product in country B, need only have the product tested by a CB (certification body) testing laboratory in his home country. The CB test report will be accepted by the national CB (NCB) in country B and used to grant any required certification marks. Since 2009, testing to IEC62471 under the IECEE CB scheme LITE category (which requires testing to a number of other standards) is mandatory for LED-based GLS products.

In China, the mandatory CCC mark

scheme requires testing of luminaires, for which IECEE CB test reports are currently accepted: through this certification route, testing to IEC62471 can be said to be mandatory for LED-based GLS products for sale in the Chinese market.

Furthermore, in many countries throughout the world, voluntary product-mark schemes are in existence. These are used to enhance the status of a product, by providing the consumer with increased confidence in its quality. Examples of such schemes include the UK BS kite, the German GS, the ENEC mark and the Korean KS mark, which are increasingly taking account of photobiological safety through application of IEC62471.

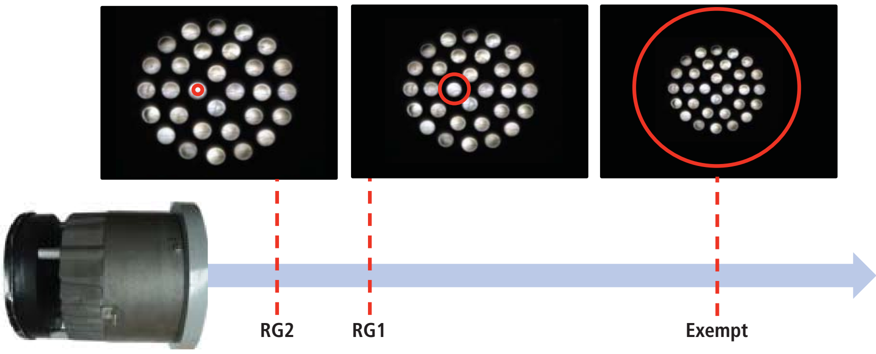


FIG. 2. Area of source seen by each blue-light RG at determined hazard distance.

Future prospects

The revision of IEC62471/ CIE S009 by IEC TC-76 and CIE D6 is underway, yet given the proposed adjustment of certain exposure limits by ICNIRP (and the correction of the current retinal thermal hazard weighting spectrum) a publication date for the update has not yet been given. Two additional parts to the IEC62471 series are being drafted by IEC TC-76, including part 4, related to guidance on measurement methods. The CIE D6 has also formed working groups with terms of reference to consider the implementation of IEC62471.

In addition to this, the European Commission has asked the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) to look into the health effects of artificial light: it will be some time before this study reports its findings.

LEDs may not represent as great a hazard as lasers, yet given their widespread use and ever-increasing optical performance, it is correct that account should be taken of the potential hazards associated with these sources. One should also be aware that while IEC62471 is based on normal behavior, and the innate aversion response, consideration should be made of those overcoming the aversion response, particularly in the case of children who have a natural curiosity and no appreciation for potential hazards.

Reports of the potential effects of chronic blue-light exposure, resulting in age-related macular degeneration and loss of vision in the central visual field, are fairly well supported (but in need of much further research). However, there have only been a few contentious reports relating to acute exposure to LEDs, including ostensible retinal damage due to exposure to a violet LED and the suggestion that LEDs may be particularly dangerous for children, whose undeveloped lenses do not offer the retina sufficient protection in the UV.

As a last note to finished-product manufacturers, while little can be done to circumvent irradiance-based hazards (other than limiting access to the source), physiological radiance can be modified by design, by minimizing the optical power in a given FOV through appropriate spacing of the LEDs and using more low-power LEDs to do the job of a single high-power chip.

Low-voltage LED lamps present unique driver challenge

MR16 sockets present a significant retrofit-lamp opportunity for LEDs, explains **KAMAL NAJMI**, but installed transformers complicate the design of a drop-in SSL replacement.

There is an enormous potential market for LED-based retrofit alternatives for legacy MR16 bulbs. But the varied electronic and magnetic transformers used to drive the halogen incandescent filaments in the legacy lamps aren't a good match for LEDs. For lamp makers to deliver drop-in, solid-state lighting (SSL) replacement lamps and the energy savings and long life afforded by LEDs, the lamp designers will have to develop a universal driver circuit. An inverting buck-boost topology appears capable of the low-voltage MR16 challenge.

In terms of installed units, few sockets can rival the MR16 halogen light bulb. MR16s can be found in homes, offices, hotels and retail shops. There are actually two classes of such lamps (shown in Fig. 1). The lamp on the left has GU-5.3 pins and is powered by a transformed low-voltage AC input. The lamp on the right is powered from the AC main and uses GU-10 pins.

We will focus here on retrofits for low-voltage lamps as such products have offered numerous advantages leading to broad usage. For example, operating from a low-voltage AC source has allowed the use of thick filaments that do not snap as easily from mechanical shock or burn out as quickly as their AC-mains-connected cousins.

Designing a low-voltage retrofit is complicated by the fact that a transformer is part of the picture. Indeed millions, perhaps billions, of low-voltage transformers are installed inside lamp housings, behind walls and in ceilings. Building owners and consumers have no desire to remove the transformers and install a brand-new system designed specifically for LEDs. A true drop-in LED retrofit would be far less costly and still offer energy savings and long life.

KAMAL NAJMI *is a Senior Power Electronic Engineer at Texas Instruments.*

FIG. 1. A low-voltage, 3W, LED MR16 with GU-5.3 pins (left), and a 230-VAC, 50W, halogen MR16 with GU-10 pins (right).

The transformer challenge

There are two basic types of transformers used to step the mains AC voltage (120 VAC_{RMS} in North America or 230 VAC_{RMS} in the rest of the world) down to 12V. The older technology is a magnetic transformer, consisting of a ferromagnetic core and primary and secondary windings on the core. The second, newer technology, is the electronic low-voltage transformer (ELVT). The ELVT is really not a transformer but a switching-converter circuit that presents a much bigger challenge to designing an LED retrofit lamp. A drop-in replacement lamp must work with both types of transformers and there are many different design schemes used in ELVTs that further complicate the situation.

An electrical engineer who takes a first glance at low-voltage AC lighting is likely to assume that the task is simple, especially compared to bulbs with mains AC inputs. ICs such as DC-DC converters with constant-current outputs for LEDs are plentiful in the range of working voltages up to 30 VDC. Since 12VAC_{RMS} is about 18V peak, a simple diode bridge and a holdup capacitor are all that are needed to provide a fairly stable DC input voltage. The DC-DC converter can then be called upon to reject any ripple and deliver constant current to a varying number of LEDs.

Digging deeper into SSL MR16 lamp design reveals several cracks in these early assumptions, and it is for these reasons that a truly universal, drop-in retrofit LED MR16 is still not available. We will focus primarily on the electrical challenge taking into account mechanical and thermal limitations of the MR16 form factor. There is a tiny vol-

ume of space available in the lamps for the control and power circuits, and the size limits the amount of heat that can be dissipated.

The amount of capacitance needed for the classic diode-bridge and capacitor circuit can dictate a capacitor that is too large to fit into the shell of an MR16 bulb. Moreover, aluminum electrolytic capacitors are the only types that deliver the multiple hundreds of microfarads needed at the working input voltage of 18V, and those components are both bulky and prone to short lifetime when exposed to the unavoidable heat of the LEDs and power electronics.

Many existing LED MR16 lamps use the simple diode-bridge approach despite the liability of the capacitor. And in many cases this basic, low-cost design will work with magnetic transformers. Magnetic transformers are still often used in wet locations such as in outdoor garden-path lighting. Still the solution is less than ideal even in the case of a magnetic transformer because current spikes can damage or degrade both the LED driver electronics and the transformer, and can reduce the lifetime of the lamp.

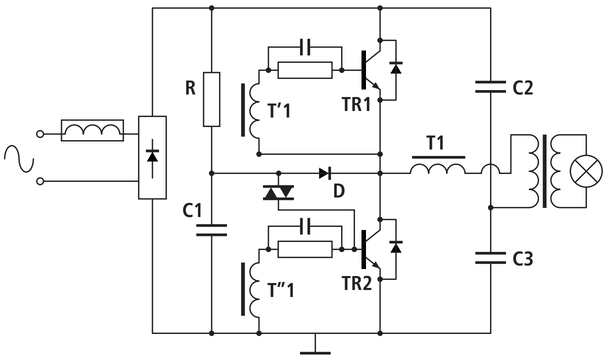


FIG. 2. Typical self-resonating, half-bridge circuit for ELVTs.

Electronic low-voltage transformers

The ELVT presents a more difficult problem. Moreover, many makers of MR16 lighting systems have transitioned to ELVTs as a lower-cost, smaller, lighter, and generally more-power-efficient alternative to magnetic transformers. An ELVT switching converter operates over a range from 30 kHz to over 100 kHz. A small magnetic transformer forms part of the circuit to provide galvanic isolation. There are ELVT controller ICs available, but the cost constraints that accompany high-volume products such as MR16 lighting systems mean that most ELVTs used in lighting applications don't have an IC or, for that matter, a control loop with a feedback circuit like the ones found in DC-DC or AC-DC power supplies. Instead, most ELVTs are self oscillating, using the half-bridge topology shown in Fig. 2.

Rather than producing a simple 50- or 60-Hz sine wave with an amplitude of $12VAC_{RMS}$, the ELVT output consists of an

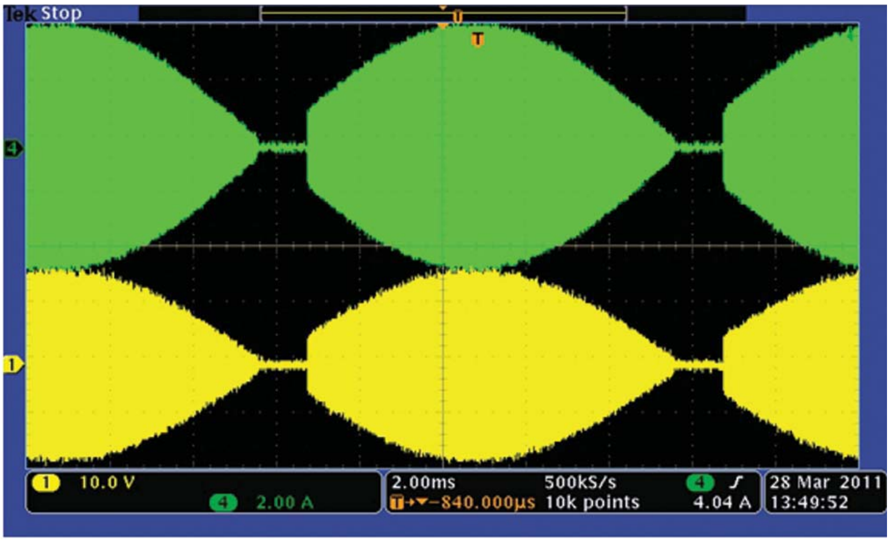


FIG. 3. Lamp input current (top) and output voltage (bottom) of an ELVT driving a single 35W halogen MR16 bulb.

oscillation at the switching frequency that forms an envelope at the desired amplitude and line frequency. Fig. 3 shows a typical waveform from an ELVT driving a single 35W halogen MR16. The top plot is the current into the MR16 lamp, and the bottom plot is the output voltage of the ELVT.

The plots reveal a key problem with ELVTs and LEDs. A typical low-voltage, halogen MR16 lamp draws anywhere from 25W to 50W. From an electrical standpoint the lamp load appears somewhat inductive, but mostly resistive. The ELVT is designed for that load.

In the region of each zero crossing in the signal envelope, even the relatively heavy load of a series of 50W halogen bulbs is not enough to get the converter started until a minimum voltage is reached. You see this in the dead zone following the end of each AC half-cycle in the plot. The ELVT doesn't operate for some amount of time at the start of the subsequent half cycle.

A typical SSL MR16 uses three 1W LEDs and has an average-quality DC-DC converter LED driver circuit with a power efficiency of 80%. The input power is only 3.75W. To make matters worse, the impedance of a closed-loop DC-DC converter that might be used in the LED lamp is negative. The negative impedance is due to the fact that a closed-loop, switching converter draws less current as the input voltage increases and vice-versa, the opposite of how a resistor, or a halogen lamp, behaves.

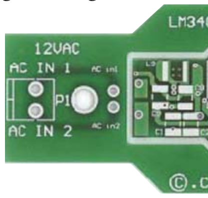
A self-oscillating ELVT that was designed for a heavy resistive load, but is instead presented with a light load with negative impedance, can result in flickering light, audible buzzing, or a complete failure to start up. Our experiments show that a typical ELVT failed even when loaded with three 4W LED lamps. With a fourth 4W lamp added, the tested ELVT operated as intended.

Zero crossing problems

The zero crossings of an ELVT output can also prove problematic to the DC-DC converter in an LED MR16 lamp. Below some minimum voltage amplitude, the switching-control circuit in the converter will fail to operate. The result can be a DC-DC converter that is inactive for a significant portion of each half cycle.

The described problem means that the buck regulator (a component widely used to drive LEDs) can't be easily used in an MR16 lamp without a holdup capacitor to keep the converter running through dead zones. But as mentioned earlier the capacitor may not fit in the MR16 form factor. Moreover, a large holdup capacitor distorts the input impedance, making undesired oscillation or large current transients more likely.

A boost converter is also ineffectual because such a design can only step-up the output voltage. Temporary high-voltage peaks could create instances of uncontrolled current to the LEDs. To get the longest operation of the LED driver during each AC half-cycle and maintain control over LED current, a topology capable of stepping the output voltage both up and down is needed.



Inverting buck-boost regulator

One approach to the problem is an inverting buck-boost regulator. Fig. 4 shows the complete circuit schematic of a buck-boost, LED-driver circuit used to solve the input-voltage, zero-crossing problem. Each LM3409 circuit draws an average input power of 4.9W while driving three white LEDs in series. The LM3409 is normally used to control a buck-regulator-based, constant-current LED driver, however by connecting the main inductor as shown in the schematic, a negative output voltage is developed with respect to the input voltage. More importantly, the absolute value of the output voltage can be greater than or less than the input voltage.

The control IC is referenced to the negative output voltage by connecting both the ground (GND) and the thermal pad (DAP) to the negative output. The LM3409 employs a variable-switching-frequency scheme that controls both peak current and peak-to-peak ripple current through the main inductor.

In buck regulators the average output

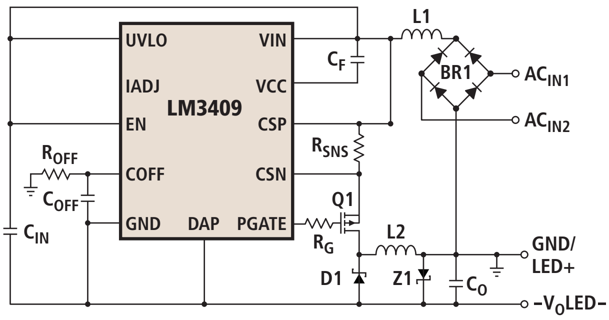


FIG. 4. The LM3409 implements an inverting, buck-boost LED driver.

current is equal to the average inductor current, hence LED current is kept constant. When the LM3409 is used as a buck-boost, however, two important characteristics change. First, in the buck-boost converter, average output current is no longer equal to average inductor current. Instead, the two quantities are related by a relatively simple equation that in fact makes output current directly proportional to input voltage.

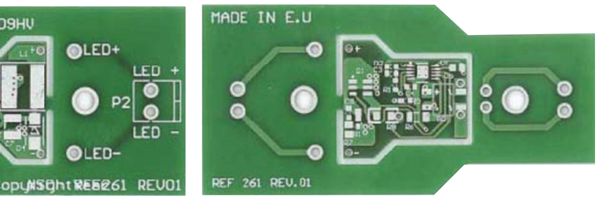


FIG. 5. The driver circuit outlined in white fits the MR16 form factor.

Controlling the output current in proportion to the input voltage forces input current to be inversely proportional, which helps get ELVTs started by drawing a heavier load at the beginning of the AC half cycle where voltage is at or near zero. It also helps keep enough current flowing to keep ELVTs operating at the end of the AC half cycle, thereby delivering current to the LEDs over as much of that half cycle as possible.

An example driver circuit board (Fig. 5) demonstrates the applicability of the proposed topology to the MR16 applications. The outlined area in the photo is 20 mm long and the shape is conducive to MR16 usage.

EMC, inrush current and reliability

The proposed driver is able to operate with many ELVTs, even if only one bulb is connected, and provides additional benefits. The minimum of input capacitance and the use of input inductor L1 help to minimize the inrush-current spikes seen mostly at the beginning, but also at the end of each AC half cycle. Needing only a few microfarads of capacitance at both input and output means that no aluminium electrolytic capacitors are needed.

Low-voltage MR16 LED lamp design remains a challenge. Every ELVT is different. In the experience of the author, the price paid for a particular ELVT does not always correspond to the quality of the performance with light loads such as LED MR16 lamps. The investigation for this article was performed with four different ELVTs, all purchased on the open market, each of which was rated for an output power ranging from 10-20W on the low side to 60-70W on the high side. A single LM3409 buck-boost circuit operated properly with all four units. However, an additional ELVT rated for a minimum of 50W refused to start up at all. Therefore, a general guideline when selecting an ELVT for use with LED MR16 lamps is to buy one with the lowest minimum power rating available.

last word

Color-quality standards bodies need to consider the broad user base

Work on a new and improved measure of color-rendering quality has apparently stagnated in the CIE, and the failure leaves the broad lighting community without a tool that would be very useful, says **MAURY WRIGHT**.

Amazingly, after nearly half a century, the lighting community is still using color-rendering index (CRI) as a measure of how accurately colors appear under a light source. CRI usage continues despite broadly recognized flaws. Moreover, there are clearly better alternatives such as the color-quality scale (CQS) developed within the US-based National Institute of Standards and Technology (NIST). Unfortunately, the use of CRI appears certain to continue for the near future as the International Commission on Illumination (CIE) technical committee (TC) 1-69 has failed to endorse CQS, or an alternative, preferring to disagree rather than deliver a tool that would be truly valuable to the broadest segment of the lighting industry.

The TC 1-69 committee had apparently come close to endorsing a dual standard last summer, according to chairperson Wendy Davis. The committee couldn't agree on a single metric, with some preferring the relative simplicity of the math that underlies CQS, and others wanting a far more precise measure of color rendering.

The committee had tentatively agreed to recommend two different metrics: CQS, and a more complex metric called nCRI that was under development at the University of Leeds, UK. Presumably, the broad lighting segment would have used CQS, while nCRI would have served in more specialized applications. Davis said nCRI would "very accurately quantify how different objects appear under the test lamp relative to a reference illuminant."

Unfortunately, according to Davis, the CIE had adopted a new Code of Procedure that required unanimous agreement within a committee before it could publish a technical report. And when the dual-metric recommendation was circulated to the full committee, a dissenting minority stopped the process.

Apparently the politics in the committee have worsened. Davis doesn't expect movement in the short term. She said the final version of the nCRI spec has just been distributed to the committee this past December.

Davis has since moved on from NIST to take a professorship at the University of Sydney, but that hasn't impacted her work on color standards. Last year at Strategies in Light, Davis said that if the CIE committee didn't agree on a new metric, then she would pursue a CQS standard elsewhere. Davis said recently, "If the CIE fails, I still plan to pursue standardization of the CQS in another organization, most likely in the US." She also said that an Illumination Engineering Society (IES) color committee was contemplating the issue, although she doesn't expect swift movement, in part because the committee is relatively new.

Now in terms of full disclosure, I'm not a color expert nor did I sit in on the TC 1-69 meetings. But I do have broad experience watching standards bodies debate while an industry anxiously awaits their work.

I know Davis has a vested interest in CQS given that she helped develop it. But I haven't heard anyone argue that CQS would not be a significant upgrade from CRI. The committee members should have voted with the best interests of the industry in mind rather than their special interests.

The CQS proposal relies on a more realistic set of color samples than does CRI, including richer saturated colors. CQS eliminates the issue of sources with extreme CCT values achieving good CRI scores. And while CQS penalizes reductions in chroma, it doesn't penalize sources that increase object chroma relative to the reference.

Meanwhile, we continue with CRI. Fortunately more lighting companies are publishing CRI numbers for some of the more-saturated color samples rather than just the composite score based on the pastels.

Still, the very best LED-based sources and fixtures sometimes get penalized in CRI scores for rendering colors that appear even richer than with the reference illuminant. That's just wrong and the solid-state lighting (SSL) industry needs a solution. Ironically, LEDs were long criticized for poor CRI, and now the manufacturers have greatly improved quality. But that improvement isn't necessarily recognized in a CRI system that was in essence calibrated for fluorescent sources.