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ARCHITECTURAL LIGHTING

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**INSIDE:** AS A MARKET TRANSFORMING TECHNOLOGY, LEDS REQUIRE A NEW LOOK AT FLICKER, DIMMING, COLOR, OPTICS, AND CONTROLS

# SOLID-STATE LIGHTING



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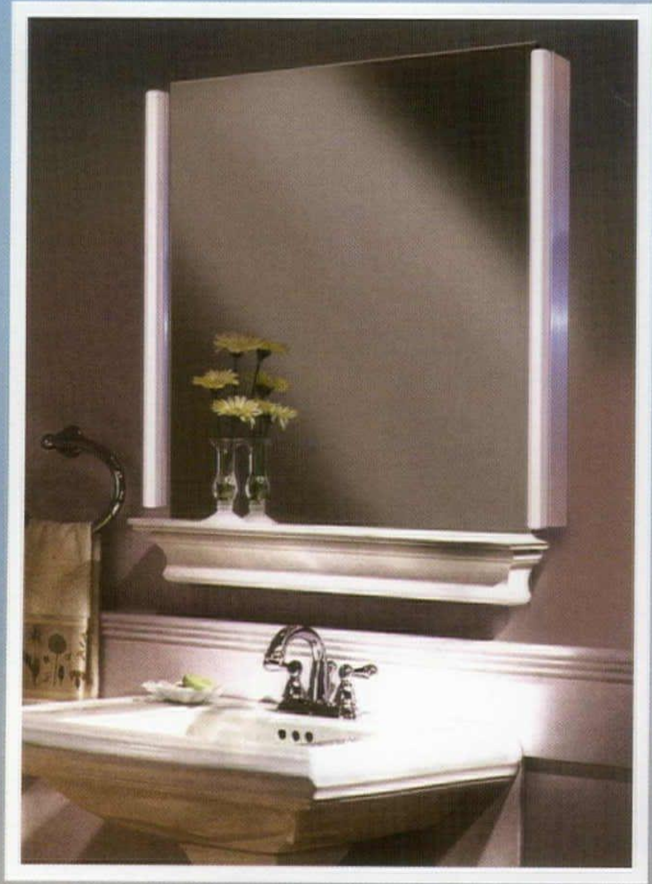
# Alinea® LED

U.S. Patent # D 672,083 S • E.U. Patent # 001973132-0001



Due to the new EISA legislation here in the U.S. and the Energy Directives abroad, the manufacture and importation of inefficient, incandescent lamps has been restricted. This applies to the Osram Linestra® or any other brand of linear incandescent architectural tubes using 2xS14s sockets.

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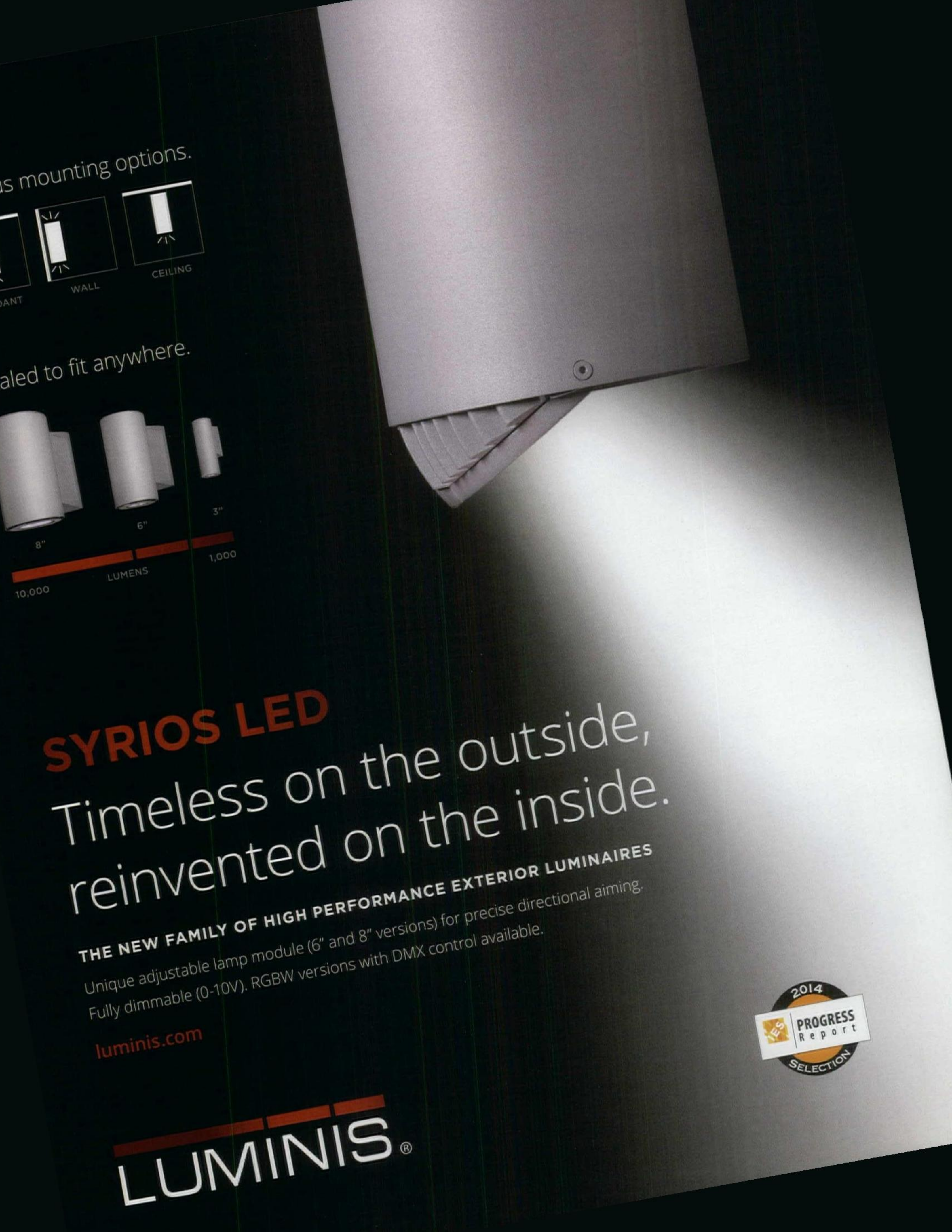

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# ·CONTENTS

## TECHNOLOGY



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# LEDS: LIGHTING'S TECHNOLOGY TRANSFORMATION

"As LEDs enter the mix, there is a need to revisit foundational lighting technology issues as they specifically relate to solid-state lighting."

**Light-emitting diodes (LEDs)** are transforming every aspect of lighting, from the way in which the design community thinks about light to the way in which the lighting industry does business. In this special supplement, ARCHITECTURAL LIGHTING gathers our widely read LED technology article series, creating a must-have reference guide for anyone working in architectural lighting design today.

Launched in 2014, the five-part series that you'll find on the pages that follow has thus far examined the topics of flicker, dimming, color, optics, and controls. These topics have always been important technical considerations in lighting, no matter what light source was being utilized. As LEDs now enter the mix, there is a need to revisit these foundational technology issues as they relate specifically to solid-state lighting. Our LED series does just that, each article focusing on a single topic, explaining the core issues surrounding that discussion and outlining the new challenges posed by solid-state lighting sources.

Also, on page 32, you will find a Resources guide, which provides an introductory list of reference materials—articles, white papers, and testing reports—that discuss the latest developments related to all of these technical issues. Throughout the articles, you will also hear from manufacturing experts, as well as leading scientific and research and development investigators, who offer their insight and knowledge on the topics at hand.

This special reprint has been created to serve as an editorial reference companion that presents critical LED technical issues in an approachable format. We are confident that it will serve as a foundational resource for anyone working in and specifying products for architectural lighting design.

Stephen Voss

Elizabeth Donoff, Editor-in-Chief
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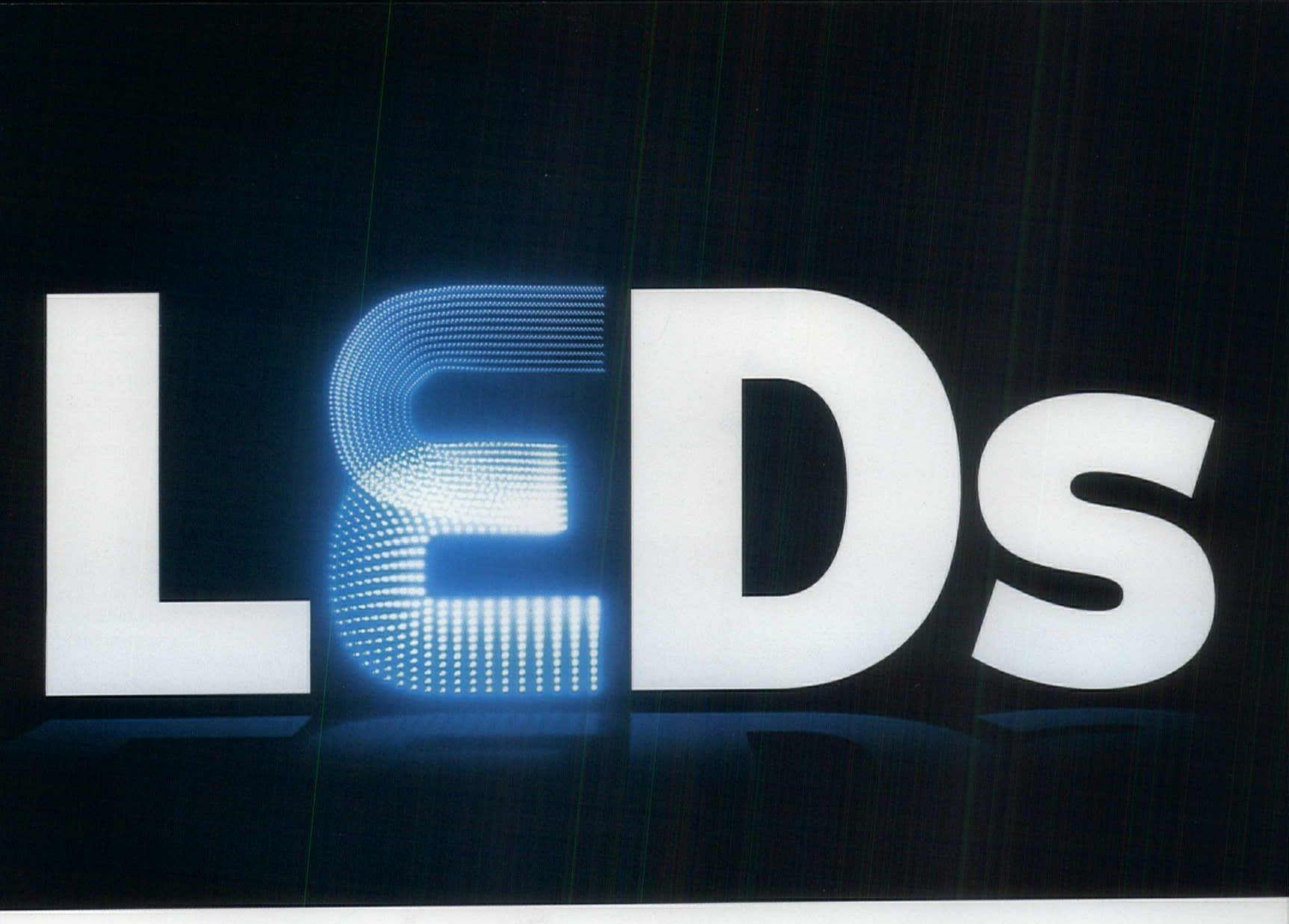



TECHNOLOGY

# FIGHTING FLICKER

**The onset of LEDs in lighting has brought manufacturers and designers back to the drawing board to discuss an age-old problem.**

text by Wanda Lau

illustration by AnotherExample

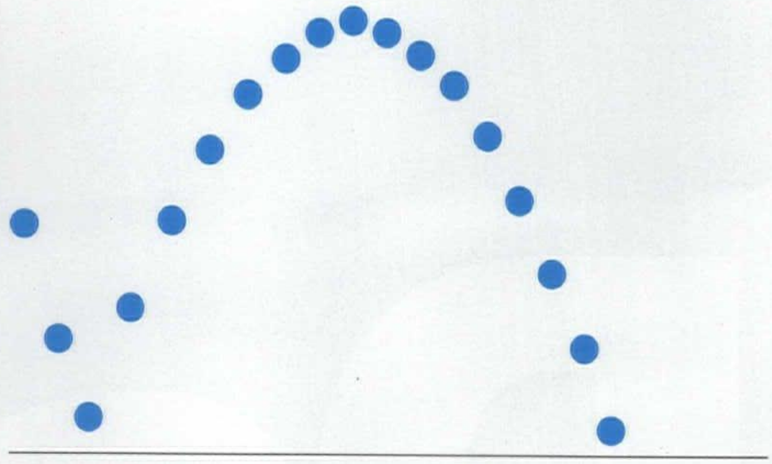
**From headaches** to underexposed photographs, the consequences of flicker can manifest in many ways. Though the lighting industry has readily adopted solid-state lighting as the energy-efficient source of today and tomorrow, it has generally fallen short in addressing the causes and effects of periodic modulation in LEDs. If left unchecked, flicker can lead to a host of problems that can ruin an otherwise well-designed luminaire or space. Understanding the basics behind the issue will help architects and lighting professionals avoid the annoying and even harmful effects of oscillating light.

### WHAT IS FLICKER?

In its simplest definition, flicker is the constant fluctuation of light output from on to off. Because electricity is delivered through alternating current (AC) at a power line frequency of 60 hertz in the U.S., the voltage delivered to a source bounces between on and off as it rides the sine wave between the positive and negative poles. As a result, the potential flicker frequency is twice the power line frequency, or 120 hertz. Without the proper electronic circuitry—such as a ballast, driver, or capacitor—a source will flicker.

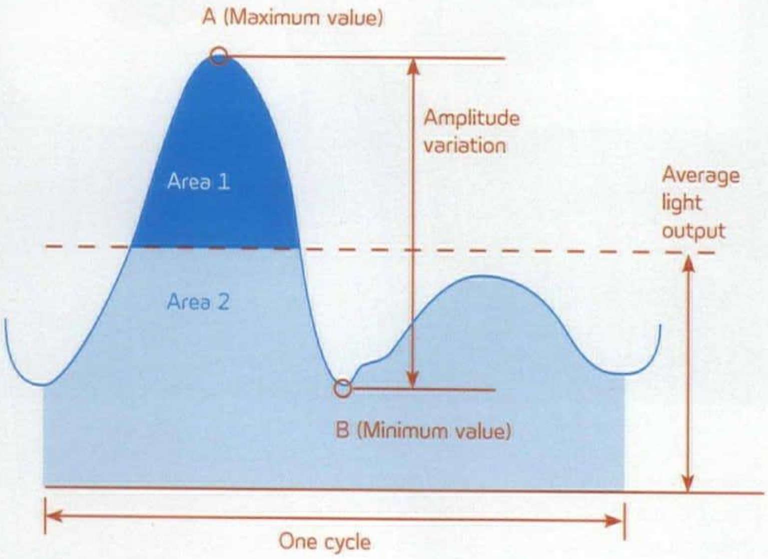
Flicker can be intentional, as in the case of oscillating bicycle headlights. "There are degrees of flicker that no one notices and are not neurologically a problem, and [there are] degrees that really are a problem," says Naomi Miller, lighting designer and senior scientist with the Advanced Lighting Team at the Portland, Ore.–based Pacific Northwest National Laboratory (PNNL). The lighting industry, she says, is "concerned about certain [frequency] ranges that can cause neurological problems in individuals or can affect task performance."

Humans can perceive light oscillation at frequencies slower than 50 hertz, although some people notice it up to 100 hertz, says Nadarajah Narendran, director of research at the Lighting Research Center (LRC) in Troy, N.Y. Slow frequencies, of approximately 3 to 70 hertz, can cause seizures in highly sensitive individuals, while moderate flicker frequencies, from about 100 hertz to as high as 500 hertz, can lead to indirect perception of stroboscopic



The stroboscopic effect can make objects in motion appear stationary or slow moving.

## Calculating Flicker Metrics




$$\text{Percent flicker} = 100\% \times \frac{A-B}{A+B}$$

$$\text{Flicker index} = \frac{\text{Area 1w}}{\text{Area 1} + \text{Area 2}}$$

## Flicker Metrics for Common Sources

| Technology | Percent Flicker | Flicker Index |
|---|---|---|
| Incandescent lamp | 6.3 | 0.02 |
| T12 linear with magnetic ballast | 28.4 | 0.07 |
| Spiral compact fluorescent lamp (CFL) | 7.7 | 0.02 |
| Quad-tube CFL with magnetic ballast | 37.0 | 0.11 |
| Quad-tube CFL with electronic ballast | 1.8 | 0.00 |
| Metal halide lamp | 52.0 | 0.16 |
| High-pressure sodium lamp | 95.0 | 0.30 |
| Direct current LED | 2.8 | 0.0037 |
| LED with significant flicker | 99.0 | 0.45 |

effects, in which objects in motion can appear as a series of still images. But what may be desirable in a dance club can be dangerous in an industrial setting. For example, flicker can make moving gears or blades look slower or even stationary, and it has been associated with adverse health effects such as headaches, eye strain, and fatigue.

As the flicker frequency increases into the kilohertz range, around 2 kilohertz and higher, preliminary research suggests that "we can no longer detect it," says Jim Benya, principal at Davis, Calif.–based Benya Burnett Consultancy. "It no longer becomes a problem." Achieving these high frequencies with different sources, however, can be a problem.

### MEASURING OSCILLATION

Currently, there is no official standard procedure for manufacturers to measure flicker, but the Illuminating Engineering Society (IES) has developed two metrics to quantify flicker that are described in *RP-16-10, Nomenclature and Definitions for Illuminating Engineering*. The first and more commonly used metric is percent flicker. It indicates the average amount of modulation, or reduction, in light output over a single on–off cycle. A source with 100 percent flicker would indicate that, at some point in its cycle, it produces no light, while a completely steady light would have zero percent flicker.

The other metric is the flicker index, which ranges from zero to one. It accounts for the percent flicker and two other variables: the shape of the light's waveform, or output curve, and the duty cycle, which refers to the percentage of time that the light source is on in a single on–off cycle. The lower the percent flicker and flicker index, the less a source oscillates or produces perceptible stroboscopic effects.

### FLICKER IN CONVENTIONAL SOURCES

All AC-powered sources flicker. In high-intensity discharge (HID) lamps, Benya says, flicker became patently obvious during the 1972 Olympic Games when photographers discovered that many of their pictures were pitch black "because they tried to take a very short exposure picture at exactly the wrong time, and the lights would be effectively off." A three-phase lighting distribution system, in which adjacent sources are pulsed 120 degrees out of phase—such that one lamp is turning on while another is turning off, and a third is somewhere in between—solved the issue of flicker in stadium lighting.

Even the beloved incandescent lamp flickers. We don't notice it, however, because thermal persistence, the same trait that makes incandescent lamps energy inefficient—about 90

Source for graph at left: Modified from *The Lighting Handbook*, IES (10th ed., 2011).
Source for table at right: Michael Poplawski, Naomi Miller, PNNL (2011); Michael Grather, Luminaire Testing Laboratory (2009)

percent of the electricity used is lost as heat—masks the effects of flicker. After the power is cut, the residual heat in the filament holds its glow until the next burst of power is delivered.

This isn't the case for fluorescent lamps and LEDs, however. "These lighting sources react very quickly to power," Benya says. "So when there's no power, there's no light." In the 1990s, magnetically ballasted fluorescent lamps came under fire for their flicker. Manufacturers resolved the problem by moving to electronic ballasts, which operated the lamps above 20 kilohertz, well above the frequency at which people notice flicker.

**WHY DO LEDS FLICKER?**

When a new source comes to market, the issue of flicker bubbles to the surface. However, LEDs may oscillate in light output even more than incandescent or fluorescent lamps did, says PNNL's Miller. Unlike HID or fluorescent, solid-state lighting is a direct current (DC) device, meaning that as long as constant current is supplied, the LED will illuminate without flicker, Benya says.

In the case of a simple LED circuit in which no constant current regulation is implemented vis-à-vis a driver, the LED's brightness will vary in phase with the cycle of the alternating current. When a driver exists, it presents both a source and a solution. Rectifying the AC to DC conversion causes a ripple in the voltage and current output from the driver to the LED. This ripple typically occurs at twice the frequency of the incoming line voltage—120 hertz in the U.S. The LED output then correlates with the output waveform of the driver.

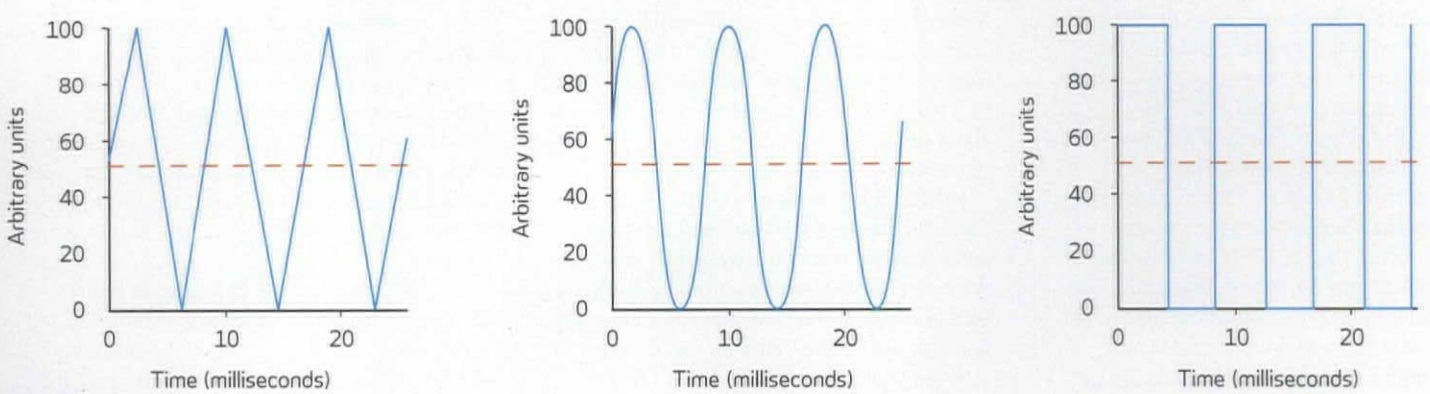
Dimming is the other primary cause of flicker. Conventional dimmers, such as TRIAC (meaning an electronic component that can conduct current in either direction) dimmers, modulate the current by extending the off time in the on–off cycle, reducing light output. Pulse width modulation (PWM) dims LEDs by turning them on and off at frequencies that ideally exceed 200 hertz. However, Benya says, "if you do PWM at a low enough frequency, such as our normal power line frequency, then once again, we've introduced a very high percentage of flicker."

**MINIMIZING FLICKER**

The key to mitigating flicker thus lies in the driver, which can eliminate the problem by supplying the LED with a constant, non-oscillating current. But manufacturers have to weigh several factors—cost, size, reliability, and efficiency—when choosing which driver to build into their products, says Mark McClear, vice president of applications engineering at Cree. The intended use of the luminaire also plays a role—flicker may be more tolerable in certain lighting scenarios than others—in ensuring that a product also isn't overdesigned.

"Manufacturers are always trying to optimize what's good enough for this application, and how we can make it acceptable from a flicker

## Simple Periodic Waveforms Properties and Flicker Metrics




Source for chart: Michael Poplawski, Naomi Miller, PNNL (2011)

**Triangle Waveform Shape**

Percent flicker = 100%

Flicker index = 0.250

Duty cycle = N/A

**Sine Waveform Shape**

Percent Flicker = 100%

Flicker Index = 0.318

Duty cycle = N/A

**Square Waveform Shape**

Percent Flicker = 100%

Flicker Index = 0.500

Duty cycle = 50%

In an effort to simplify testing compatibility between dimmers and dimmable LED light engines (LLEs), the National Electrical Manufacturers Association (NEMA) issued *NEMA SSL 7A-2013, Phase Cut Dimming for Solid State Lighting: Basic Compatibility,* a guide for lighting designers and manufacturers.

standpoint without driving the cost point up," McClear says. A capacitor can help modulate the AC ripples from the driver to LED, but they, too, have shortcomings, Benya says. "They're large ... and they hate heat." So, in a space that is often already too tight, such as in many LED replacement lamps, a capacitor won't work.

For LEDs dimmed using PWM, manufacturers can modulate the current to a very high frequency exceeding several thousand hertz. This is similar to what electronic ballasts do for fluorescent lamps. The higher the desired frequency, however, the closer the driver and the LED physically need to be. "Unfortunately, a lot of people want to have a driver somewhat remote from their lighting system, so that isn't always possible," Benya says.

In an effort to simplify testing compatibility between dimmers and dimmable LED light engines (LLEs), the National Electrical Manufacturers Association (NEMA) issued *NEMA SSL 7A-2013, Phase Cut Dimming for Solid State Lighting: Basic Compatibility,* a guide for lighting product designers and manufacturers. Dimmers and LLEs that are compliant with the standard will thus be compatible with each other.

The standard represents a first for the industry, says Megan Hayes, a technical program manager at NEMA. Signed off on by 24 major manufacturers, *SSL 7A* aims "to get rid of matched-pair testing for lamps and dimmers," she says. The catch is that the standard only applies to forward-looking technologies and does not, as the title would suggest, provide a method to "determine compatibility with existing products or the installed base of LLEs and phase-cut dimmers."

#### SETTING THE LIMITS

On Sept. 30, the U.S. Environmental Protection Agency's Energy Star program will require manufacturers to report the highest percent flicker and highest flicker index on all of their dimmable lamps. But guidelines for what value ranges are deemed acceptable have remained conspicuously absent.

Enter the Lighting Research Center, which, in 2002, established the Alliance for Solid-State Illumination Systems and Technologies (ASSIST), a collaboration of government organizations, researchers, and manufacturers led by the LRC's Narendran. The organization took a first step toward defining acceptable oscillation rates in 2012 when it released *ASSIST Recommends... Flicker Parameters for Reducing Stroboscopic Effects from Solid-State Lighting Systems,* which includes equations to estimate the detectability and acceptability of stroboscopic effects in a source.

More recently, ASSIST sponsored a study on indirect flicker perception and human factors, conducted by LRC senior research scientist John Bullough. Having determined that frequency and magnitude of modulation are the two primary indicators of predicting people's annoyance with flicker, Bullough is trying to pinpoint "at what points do [stroboscopic] effects become noticeable and ... not acceptable for someone to constantly work under this type of lighting." For example, he says, although computer screens flicker at about 60 to 70 hertz, the flicker largely passes unnoticed.

Ideally, Bullough wants to create a reference that lists a source's flicker metrics, and the percent of occupants that would likely notice the flicker. Narendran says that the study, due to be released this year, has moved to the analysis phase to determine limits for flicker index for selected lighting applications.

#### SPEC TIPS

Lighting professionals can take some steps to reduce their chances of specifying solid-state lighting products that flicker. For interiors, be wary of products advertised as AC-LEDs, Miller says. The simpler circuit design, lack of a driver, and, consequently, low price may seem attractive, but some AC-LEDs produce up to 40 percent flicker at full output. At dimmed levels, the percent flicker can be even higher.

Replacement LED lamps, such as MR16, A-lamps, and PAR lamps, are also more likely to flicker than, say, a high-bay lamp, McClear says. The replacement lamps have space limitations, so they may rely on simple drivers that lack the necessary electronics to rectify the output.

For non-dimming applications, flicker may not be perceptible if a high-quality driver is installed. But if a designer pairs a replacement lamp with a conventional wall box or TRIAC dimmer instead of investing in a dedicated LED fixture with a zero-to-10V or digital volt-dimming system, "you're going to get flicker from even the best name products," Benya says. "Clue number one is that if you go cheap, you're probably going to have flicker."

Designers should work with lighting manufacturers to identify a compatible system and test that system firsthand under the driver and dimming settings expected in the final installation. One low-tech test, Miller says, is to illuminate a spinning top and look for stroboscopic effects. Another is to wave a pencil quickly under the light source to produce the illusion of a fan. Under a flickering light source, gaps or dark lines will be apparent in the fan; if there's no flicker, the fan will appear to be smooth, continuous, and free of gaps.

It may sound like the dark days of fluorescent lamps and magnetic ballasts have returned, but solid-state lighting that is free of perceptible stroboscopic effects does exist. Designers and specifiers have to be careful and do their research. "It's not like everything is gloomy," Narendran says. "You've got to invest the time up front to ensure that these are compatible systems that you're using." •

*Additional reporting by Heidi Moore.*

# LEDs

TECHNOLOGY

# A DEEP DIVE IN DIMMING

## By its nature, solid-state lighting can dim smoothly, but when paired with legacy technology, some outstanding issues may reappear.

text by Alice Liao

**Restaurants and theaters** have long employed dimming as a way to create atmosphere, foster a sense of intimacy, and transport diners and audiences alike. Dimming can reduce energy consumption and enhance a space's function, as in the case of a seminar room or lecture hall. But despite their ubiquity, dimmers used with conventional sources can still have problems, including a reduction in efficacy for incandescent lamps, and a reduction in longevity for fluorescent lamps.

The majority of dimming systems installed today are phase control devices. Designed originally for incandescent lamps, they reduce light output by "interrupting the current during each AC [alternating current] half-cycle," says Nadarajah Narendran, director of research at the Lighting Research Center (LRC), in Troy, N.Y., and program organizer of the Alliance for Solid-State Illumination Systems and Technologies (ASSIST) program. Essentially, phase control devices temporarily shut off power to the light source and dim voltage. In fact, they're also called phase cut dimmers because the interruptions in current create cuts in the AC sine wave.

The interruptions occur at a rate of 120 times per second, or twice the frequency at which alternating current delivers electricity over power lines. But because the tungsten filament in incandescent lamps is slow to heat up and cool down, the human eye sees the output as a constant level of decreased brightness. The longer the interruptions, the dimmer the light.

Not all phase control devices cut from the same part of the AC sine wave. A triode semiconductor for alternating current (TRIAC), which is used to dim incandescent and halogen lamps, cuts from the forward phase, which begins just as the current changes polarity and the voltage running through the circuit is zero. Also referred to as forward-phase control dimmers, TRIACs can produce spikes in current that cause dimmed lamps to buzz and add stress to electronic drivers.

Reverse-phase control dimmers avoid these problems by cutting from the latter portions, or trailing edges, of the AC waveform. By switching the light circuit on just as the current changes direction, they allow the voltage to rise gradually before turning it off later in the half-cycle. Also called electronic low-voltage (ELV) dimmers, reverse-phase control dimmers were developed to enhance the performance of halogens that use electronic transformers.

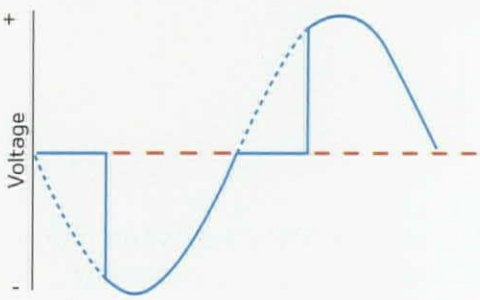
### HOW LEDS DIM

As a constant-current source, an LED is inherently dimmable. "The amount of current flowing through an LED device determines the light output," Narendran says. Their level of brightness is adjusted simply by controlling the current passing through the stacked layers of semiconductor material mounted on a substrate.

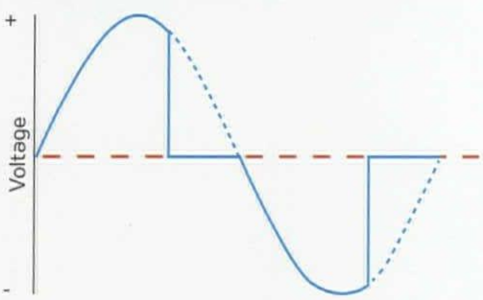
Unlike conventional sources, dimming does not affect the efficacy or longevity of LEDs, says James Brodrick, lighting program manager in the Building Technologies Office at the U.S. Department of Energy (DOE). In fact, dimming can extend the lifespan of LEDs by lowering their operating temperature.

Moreover, the dimming range of LEDs is broader than that of compact fluorescent and high-intensity discharge lamps. They can turn down to less than 1 percent of full output, compared to 10 to 30 percent of measured light output for compact fluorescents, according to the National Electrical Manufacturers Association (NEMA), and 30 to 60 percent of lamp power for

## Forward-phase control dimmer (TRIAC)




## Reverse-phase control dimmer




TRIACs cut power to the source in the forward phase, just as the current changes polarity and the voltage in the circuit is zero. Reverse-phase control dimmers cut from the trailing edges of the AC waveform.

high-intensity discharge lamps, according to the National Lighting Product Information Program.

All LED devices, be they replacement lamps or LED luminaires, require a driver in order to dim. Because they're low-voltage, direct current (DC) sources, LEDs need drive electronics to convert the alternating current that flows through power lines into a usable and regulated direct current form. These drivers dim LEDs in one of two ways. In pulse-width modulation (PWM), the current sent through an LED is switched on and off at a high frequency—"often several thousand times per second," Narendran says. "The current flow through the LED is the time-averaged value of the current when the LED is on and when it is off." Reducing the amount of time that the LED is on decreases the time-averaged current, or the effective current, delivered to the device and, as a result, its brightness.

LEDs, as well as conventional sources, can also be dimmed through constant current reduction (CCR), or analog dimming. CCR maintains a continuous current to the source, but it reduces its amplitude to achieve dimming. "The light output is proportional to the amount of current flowing through the device," Narendran says.

Both PWM and CCR strategies have their advantages and drawbacks. The more widely used PWM offers a broad dimming range, can decrease light output to values of "less than 1 percent," Narendran says, and avoids color shift by operating the LED at its rated current level—or its maximum light output—and at zero current. However, because PWM dimming involves rapid switching, it requires sophisticated and expensive drive electronics to produce the current pulses at a frequency high enough to prevent perceptible flicker.

CCR dimming is more efficient and simple to implement because of its less complex and less expensive electronic requirements. Unlike PWM, it does not have the potential to generate electromagnetic interference, which can result from high-frequency switching. CCR dimming also allows drivers to be located remotely from the light source, which is helpful in the case of LED replacement lamps or in smaller fixtures where space is an issue. However, CCR is not suitable for applications where dimming light levels below 10 percent is desired. "At very low currents, LEDs do not perform as well and the light output can be erratic," Narendran says.

### COMPATIBILITY ISSUES

Although the driver dictates whether an LED product will dim, the driver's performance largely depends on its compatibility with the dimming device, such as a phase control device. The driver must be designed to understand and interpret the signaling by the dimming device in order for dimming to occur.

Many of the dimming technologies used for conventional sources can also work with LEDs. These include zero-to-10V analog, DALI (Digital Addressable Lighting Interface), DMX (Digital Multiplex), and "other techniques that separate the dimming signal from AC Mains voltage," Brodrick says.

Installing dedicated wiring that relays dimming information to the dimming device can alleviate compatibility issues because it enables the dimmer and source to operate with little or no interference from each other. However, these types of dimming systems also tend to be more complex and expensive, which may explain why they are more common in commercial applications than in residential.

The most common phase control device is the TRIAC dimmer. NEMA estimates that there are 150 million of these installed in U.S. homes, and that these legacy devices will represent the bulk of dimming devices for replacement LED fixtures as incandescent sources are phased out. Unfortunately, the compatibility of LEDs with TRIAC dimmers is problematic.

One reason for this stems from the difference in how incandescent lamps and LEDs are powered. Incandescents produce light through simple resistive loads that draw electricity directly from the AC grid. The relationship between current, voltage, and brightness is linear and straightforward. A change in the voltage affects the current proportionally.

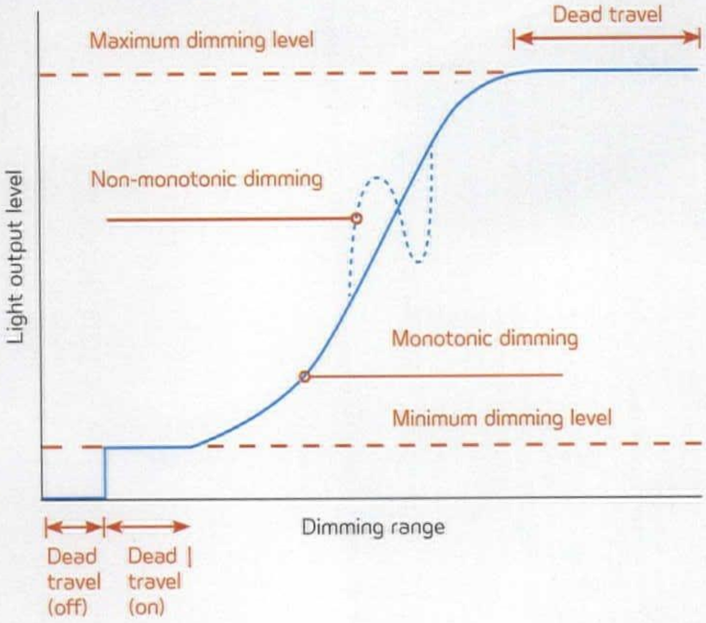
Not so for LEDs. Because the diodes rely on drive circuitry to ensure constant current and to adapt power and voltage for their use, their interactions with TRIAC dimmers are less predictable. At low dimming levels, for example, an LED driver designed to supply constant current or constant voltage may try to compensate for the phase cut portions—or interruptions in the AC sine wave—by drawing in more current, causing the LED to stay bright or to flicker.

Moreover, not all drivers are built alike. Different circuitry means different ways of drawing power, converting it, and outputting it. Consequently, pairing a TRIAC with an LED product can be "hit or miss," Narendran says. Also, "one lamp on a single dimmer might work but when several lamps are added in parallel—like in a chandelier—it may not dim well."

The opposite can be true, says Jan Kemeling, founder and chief sales and marketing officer for Ledzworld, a Dutch manufacturer of LED lighting products. He advises against mixing different LED lamps on the same dimmer because of the variety of driver designs.

The wiring for a TRIAC dimmer further exacerbates matters. Many existing and installed dimmers are two-wire devices; that is, the same wire that provides power to

## Dimming Curve




This example dimming profile shows the rate of change in light output as a function of the dimmer range. Not all of these elements may occur in a product's dimming profile.

Source: Alliance for Solid-State Illumination Systems and Technologies

the light source also conveys the dimmed voltage, or dimming signal. This can interfere with the functioning of both the LED device and the dimmer, Brodrick says. Dimmers, particularly those with additional features such as nightlights and light level indicators, have internal circuitry that require constant, albeit minimal, power even when the light source is turned off. With incandescents, this can be done without triggering illumination of the lamps. Because LEDs don't require much to power up, this is a little trickier for those devices, which may also flicker, says Michael Skurla, senior product and market manager, Americas, Indoor Global Systems, Philips Lighting Systems.

The incompatibility between LED drivers and TRIAC dimmers can cause a host of problems. Six such problems are: pop-on, in which the LED source suddenly turns completely on as the dimmer switch is raised from fully off; drop-out, in which the light source shuts off completely as it is dimmed; dead travel, which occurs when changing the dimmer setting produces no visible shift in the light level; ghosting, where light is still visible when the dimmer switch is fully off; audible noise; and flicker.

Flicker, dimming, and color shift are some of the outstanding performance issues that may prompt professional and consumer wariness toward solid-state technology. However, the lighting industry is addressing the issue of dimming on multiple fronts. Released last year, *NEMA SSL 7A-2013 Phase Cut Dimming for Solid State Lighting: Basic Compatibility* seeks to minimize compatibility issues relating to LED phase cut dimming by providing design and testing guidelines for both dimmers and LED products. However, the standard only addresses future technologies and does not attempt to regulate past dimming and lighting devices.

**DIMMING THE RIGHT WAY**

The lighting industry has also developed protocols to bring uniformity to the marketplace. Ledotron is an open digital standard launched in Europe that aims to stabilize dimming performance in systems designed for CFL and LED lamps. The nascent standard results from collaborations between several European manufacturers, including Osram and Schneider Electric.

In North America, the ZigBee Alliance's ZigBee Light Link is a standard for wireless dimming and control of LED products. Created for consumer convenience, Light Link certification ensures that lighting and light control products have plug-and-play functionality and interoperability; those that qualify bear the ZigBee Certified seal.

LRC's 2013 publication *ASSIST Recommends ... Dimming: A Technology-Neutral Definition* suggests performance criteria for dimming, regardless of lamp type, to ensure end-user visual comfort and satisfaction. It sets minimum and maximum light levels (5 percent and 90 percent, respectively), evaluates dimming profiles, and covers issues such as dead travel, flicker, and system efficacy.

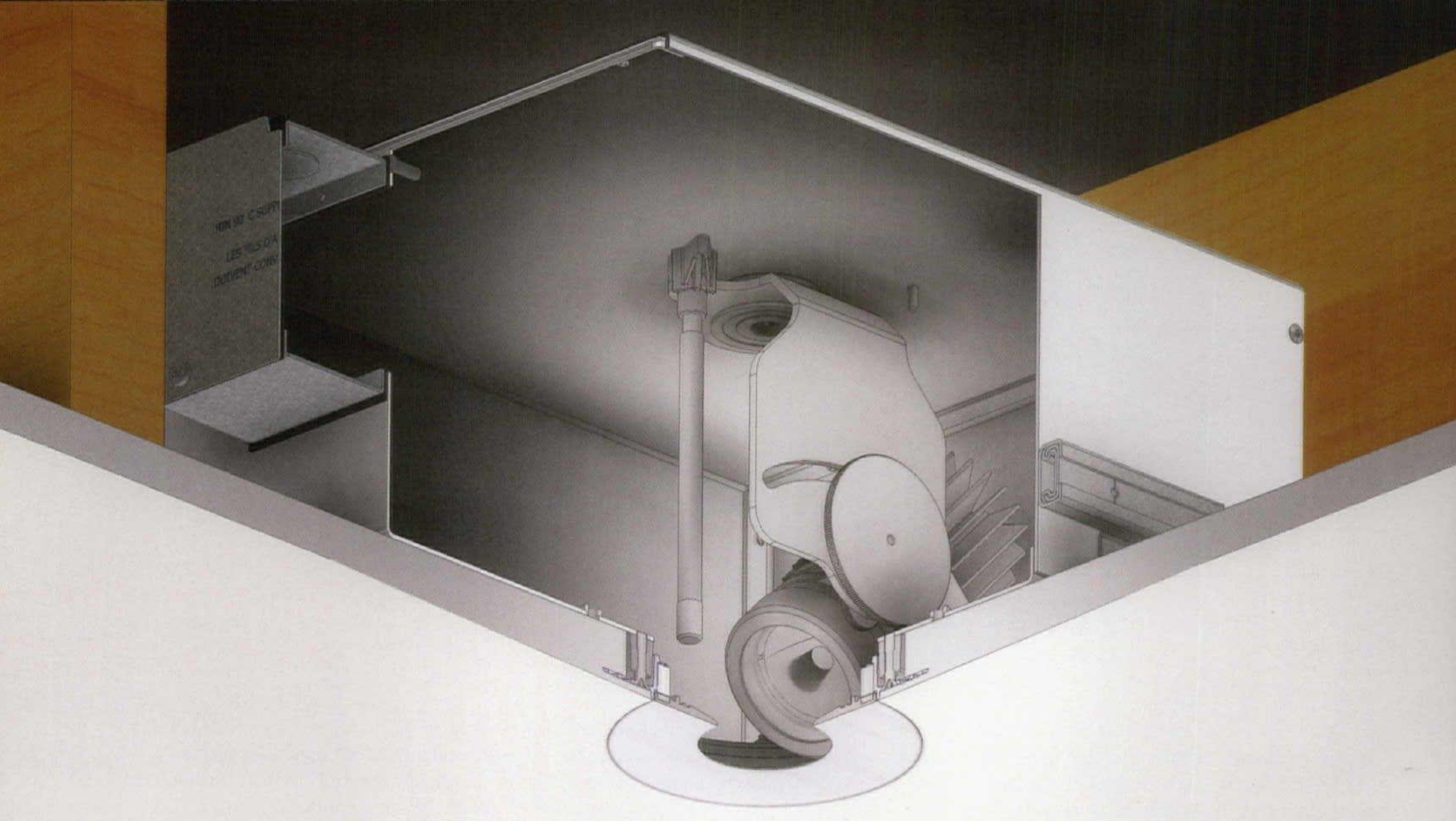
In practice, LED dimming problems can be minimized by taking certain precautions. First and foremost, designers should specify dimming control devices that are designed for LEDs. Look for LED source and dimmer combinations that are recommended by the manufacturer of either product, or both. For wall-box installations, Brodrick advises selecting a NEMA SSL-7A-compliant dimmer and LED sources.

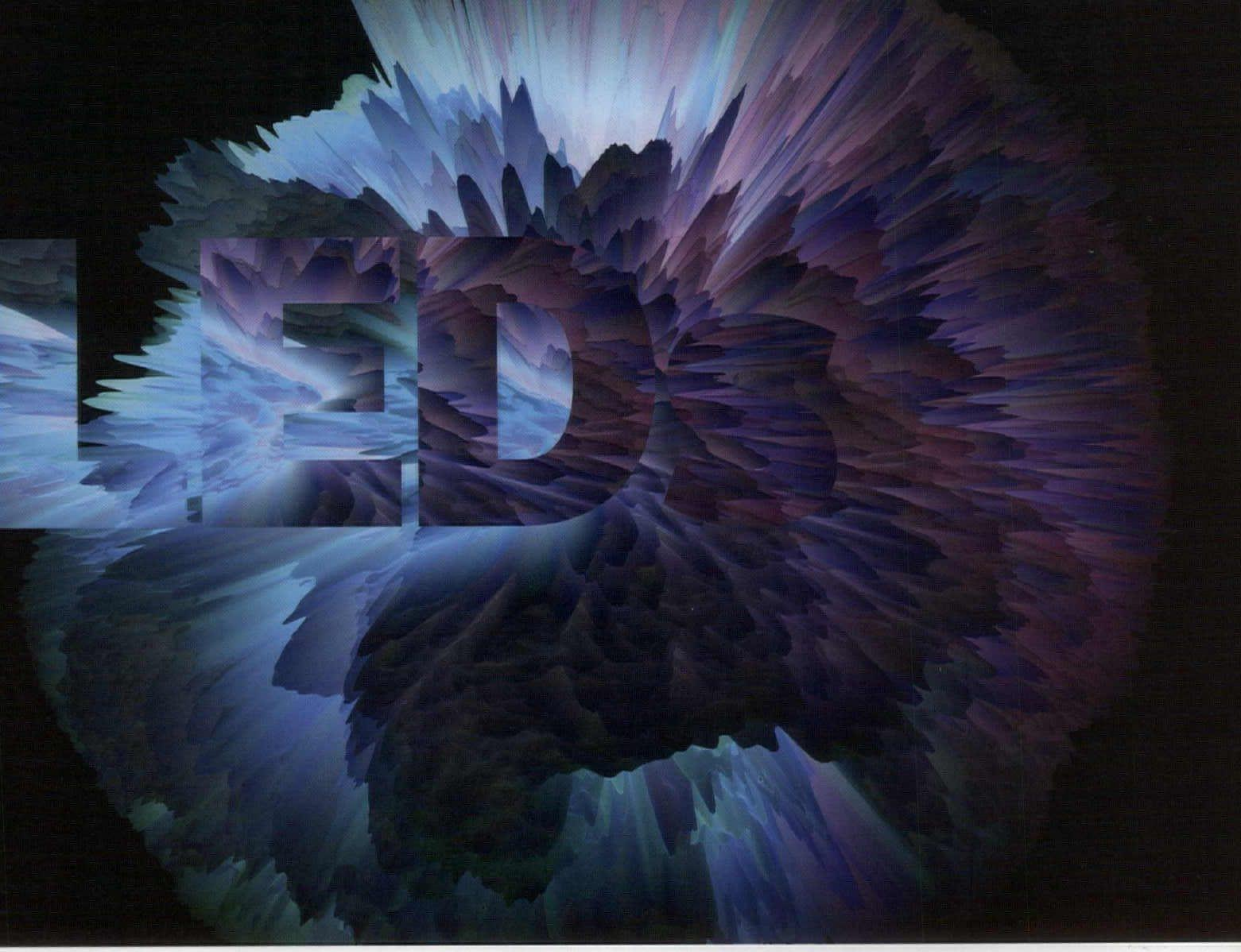
Designers should also perform a full mock-up of all lighting circuits, "including all LED sources and dimming controls, and test over the full dimming range." If a mock-up is not possible, specify a proven LED source and dimmer combination, but make sure the information is no more than six months old.

When using LEDs with phase control dimmers, designers should decrease the maximum load rating of the dimmer, usually given in watts, to minimize stress to dimmer electronics. Although LEDs are considerably more efficient than their incandescent counterparts, determining the number of LED sources that can be connected to a dimmer is not as simple as dividing its maximum load rating by watts per source.

Instead, a decrease is needed to accommodate small spikes in power caused by driver functioning. "Typical de-rating percentages should be in the range of 25 to 30 percent of the dimmer-rated power," Ledzworld's Kemeling says. A dimmer with a maximum load rating of 1,000W would, therefore, be de-rated to 250W. This could then be used to calculate the maximum number of sources that the dimmer could accommodate.

Narendran says that manufacturers are also working to enhance circuitry in both LED drivers and dimming devices for better compatibility with TRIACs. Some drivers incorporate adaptive control processing, Kemeling says. This allows drivers to synchronize with any type of dimmer, but they do cost more. So while advancements in dimming have been made, optimal performance still requires a little more time and energy. •





OLOGY

# ECODING OLOR ERFORMANCE

## -state lighting is forcing ndustry to examine tanding metrics.

Alice Liao

**Advances in LED color quality** are presenting serious challenges to the Color Rendering Index (CRI) and Correlated Color Temperature (CCT). These two metrics, developed in an era of incandescent and fluorescent lamps, are still widely used by the lighting industry to communicate the color performance of all sources. Although their limitations have long been known, the rapid proliferation of LEDs has prompted the development of better metrics to predict their specific color rendering ability.

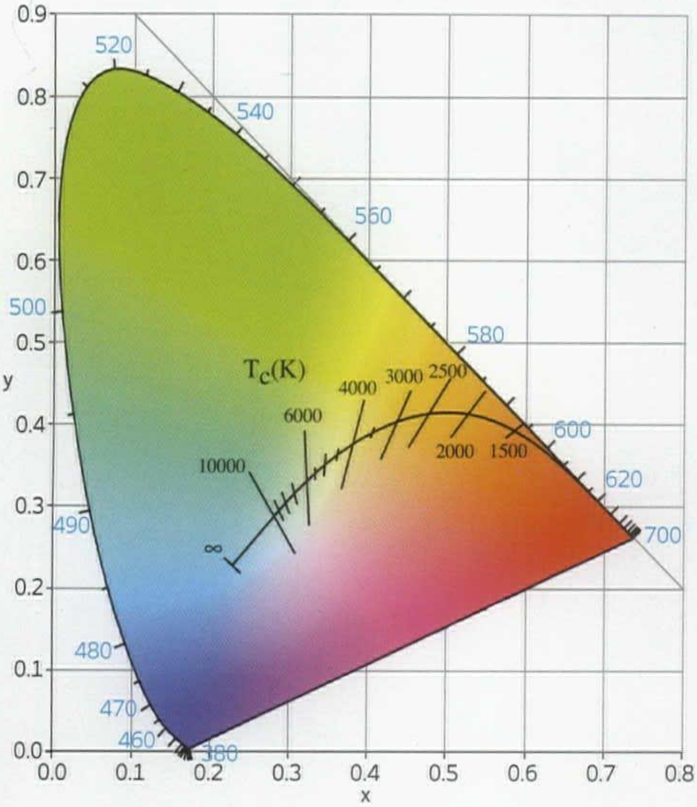
### UNDERSTANDING CRI AND CCT

CRI is particularly unreliable and, say some lighting experts, even irrelevant when applied to LEDs. Although LEDs generally have lower CRIs than conventional sources, such as incandescents, some LEDs have been shown to reproduce color more vividly and attractively—a trait that is particularly desirable to retailers. Moreover, notes Rohit Patil, a color scientist at Xicato in San Jose, Calif., LEDs offer the unique opportunity to "create a custom spectrum of lights" for specific installations, which may prove more useful than an exalted CRI.

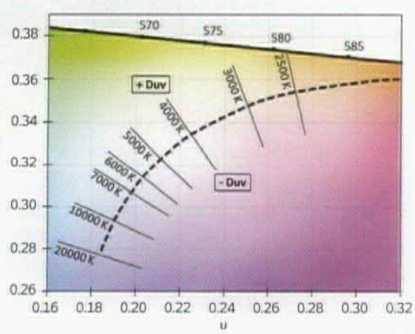
Established by the Commission Internationale de l'Eclairage (CIE) in the 1960s, CRI measures a light source's ability to reveal the intrinsic colors of the objects it illuminates. Testing is done with eight color chips, numbered R1 to R8, and the results are compared to those of a reference source of the same CCT. Sources with a CCT below 5000K are compared against a blackbody radiator—a non-reflective object that, when heated, emits a spectrum of light solely determined by temperature. Sources with a CCT above 5000K are checked against daylight.

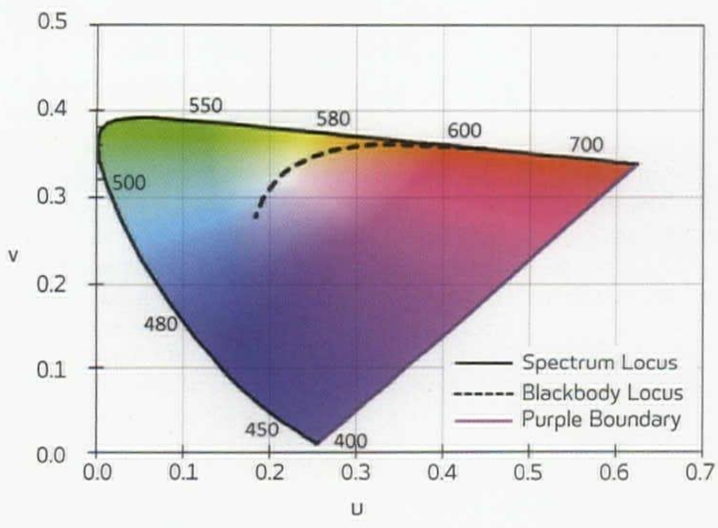
Differences in color rendition are evaluated on a scale of zero to 100, with 100 indicating a match (negative CRI numbers are rounded up to zero). A CRI of 80 or above is typically desired for indoor applications—not a difficult feat for incandescents, halogens, and metal halides, which typically have CRIs at or above 90. Many of today's LEDs are competitive, a notable achievement for a source whose CRIs topped out at 60 or 70 a mere decade ago, says Paul Scheidt, product marketing manager at LED manufacturer Cree.

## CIE 1931 (x, y) Chromaticity Diagram




## CIE 1960 (u, v) Chromaticity Diagram




The CIE chromaticity diagrams map perceived color. Lightness, the third dime the color space, is not shown in these two-dimensional graphs. The CIE creat 1960 Uniform Chromaticity Scale (UCS) to reduce the limitations of the 1931 it has since been updated by the 1976 (u',v') UCS. The Planckian, or blackbo locus—shown by the curved lines within the filled areas—indicates the color blackbody radiator emits within each chromaticity diagram as it is heated up.

CCT, the other primary metric, focuse the tint of white light exhibited by the s Measured in degrees Kelvin, it relates t color of a white light source's illuminati to the surface temperature of a blackbo radiator. Warm sources have a yellow ti and lower CCT values. Cool sources hav bluish cast and higher CCT values. Cand for example, is rated around 1850K, wh daylight exceeds 5000K.

Although CRI and CCT conveniently r the complexity of color performance to single value, "anytime we do that, we los lot of information," Scheidt says. Source the same CRI or CCT value can vary wi appearance and behavior. This is particu problematic with solid-state lighting, wh CRI has not been "very predictive" in th specification of "quality lighting," says M Rea, director of the Lighting Research C (LRC) in Troy, N.Y.

#### THE MATHEMATICS OF COLOR

Both CRI and CCT are derived through r mathematic simulation rather than throu empirical measurement. CRI testing is calculated on a computing device using a source's spectral power distribution (SPD diagram that depicts the radiant energy emits at different wavelengths of visible wavelengths of 380 to 780 nanometers— the spectral reflectance of each color chi is also computed from the source's SPD.

The math behind CRI and CCT stems f CIE colorimetry system. Though not excl to lighting, it provides the foundation for color calculations in the lighting industry regardless of source. The system is preci

## CRI Test Color Patches $R_1$–$R_8$


## Supplemental Test Color Patches $R_9$–$R_{14}$


## CQS Color Samples


Note that R15, intended to simulate Asian skin tone, is not shown because it was a late addition to the system. Due to printing variations, these colors may not render accurately.

U.S. Department of Energy

in that it measures color based on spectral characteristics rather than on appearance, which can be more subjective, contextual, and difficult to evaluate. One of the system's earliest and most commonly used mathematical models is the CIE 1931 color space, which maps all visible color to an x, y graph based on chromaticity. Chromaticity refers to a color's hue—its dominant wavelength—and saturation, and is expressed in the color space by a pair of coordinates derived from a source's SPD.

Although the 1931 standard remains in use today, updates have improved its uniformity so that calculated differences between colors are more perceptually accurate. Both CRI and CCT use the CIE 1960 (u, v) color space, but it, too, is considered outdated and the mathematics lacking in rigor, says Michael Royer, a lighting engineer with the Pacific Northwest National Laboratory's advanced lighting team.

#### LIMITATIONS OF CRI

Beyond numbers, one longstanding criticism of CRI has been the pastel appearance of the eight test colors, which "are not representative of the world," says Julian Carey, senior director of marketing at LED phosphors manufacturer Intematix Corp. Seven additional color patches, named R9 to R15, have been introduced and include a saturated red, yellow, green, and blue, as well as two skin tones and a green representative for vegetation. However, these patches are not applied to the calculation of CRI and are only recommended for supplemental information.

Equally problematic, CRI is an average of the color shifts on the eight test colors. Consequently, an LED product with standout performance on some test colors and poor rendering on others still achieves a high rating. To better inform specifications, some LED manufacturers are publishing the individual values of R1 through R15.

CRI is often mistaken as an indicator of how pleasantly colors will be rendered. In fact, it functions more as a fidelity index. Performance is rated with respect to a reference source—either a blackbody radiator or daylight—which is considered the gold standard. But this could be misleading too. "What if I can create a light source that does much better in rendering than the reference source?" Patil asks. It would likely be penalized, he says, even if "colors appear more colorful than under the reference source."

Given the strides made in phosphor-converted white LEDs, which account for the majority of LEDs used in architectural lighting applications, it may be time for a new reference source. Whereas early LEDs relied on a yellow phosphor to absorb energy from a blue diode and produce white light (often with a bluish tinge), advancements in phosphor compositions now allow the manipulation of spectral content and therefore color rendition. Some companies have replaced the blue LED with one in the near-violet region to produce a fuller, more continuous spectrum and thus colors that are more vivid and whites that are more nuanced. A fuller spectrum, however, might come at the expense of energy efficiency, as more phosphor requires more energy to convert the blue LED into white light.

#### CCT SHORTCOMINGS

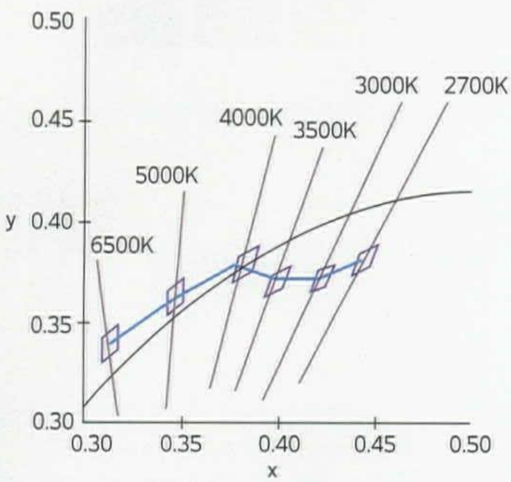
Solid-state lighting is also challenging the adequacy of CCT, but it's not the first to do so. Like other sources, such as high-intensity discharge lamps, LEDs with the same CCT can differ vastly in chromaticity and, therefore, appearance. One may have a greenish cast, while another may seem slightly pink.

While conventional wisdom suggests that light sources that cleave close to the blackbody locus appear whiter, the LRC has found otherwise. In residential applications, most people prefer whiter light than the warm output of incandescents, says Rea, who co-wrote the 2013 paper "Class A Color Designation for Light Sources Used in General Illumination" in the *Journal of Light and Visual Environment*. When mapped in the color space, the chromaticity of perceived whiteness follows an irregular path that goes both above and below the blackbody locus.

CCT can be particularly effective in assessing phosphor-converted LEDs. Manufacturers sort LEDs into bins based on the CIE 1931 color space, Scheidt says. Bin size, which refers to the area of tolerance for chromaticity differences, is measured in units of SDCM (standard deviation of color matching), or MacAdam ellipse steps. The latter takes its name from color scientist David MacAdam, who discovered that chromaticity shifts undetectable by the human eye fell within an ellipse on the 1931 color space.

The ANSI C78.377-2008 LED binning standard defines one bin size as a seven-step MacAdam ellipse. This, Patil says, is "huge" and may account for the criticism of early LEDs as having poor uniformity. "Manufacturers were making LED sources that fell into [one] bin, but looked really different." When installed side by side, they can produce a rainbow effect. Improvements and innovations in

## Class A Color Chromaticity Diagram




Sources certified as Class A Color have a white illumination (blue line) that falls within a prescribed chromaticity tolerance (squares).

manufacturing have enabled some companies to put LEDs in bins as small as one or two SDCMs. A difference of three SDCMs is noticeable by the majority of the population, Patil says.

Although bin specification is typically the purview of luminaire manufacturers, designers should know the manufacturer's tolerance for initial color consistency. A difference of three SDCMs, for example, may become even more pronounced as the number of luminaires increases. Responsible manufacturers publish this information, says Steve Landau, Xicato's director of marketing communications; if they don't, he says, "that's a big red flag."

### NEW METRICS

Given CRI's uneven history, several new metrics and classifications have been proposed that address the indexes' limitations, particularly as solid-state lighting gains a larger market share.

The National Institute of Standards and Technology's Color Quality Scale (CQS) offers improvements on multiple fronts. It is a fidelity metric that results in a single-number rating, but tests with a broader range of colors (15 instead of eight) that are higher in chroma and saturation than R1 to R15. Color preference is also considered, Patil says. "If a light source makes colors appear more colorful than does the reference source," he says, "it will have a higher number." To penalize color distortion, the CQS imposes an upper limit on saturation that, if exceeded, will lower a source's rating.

CQS uses a color space that is more uniform and its calculations are more rigorous than those for CRI, Scheidt says. CQS also factors in extreme color temperature, which impairs a source's ability to render color, and takes a root-mean-square of the color shifts of all 15 test colors rather than an average. This ensures that poor performance on a few samples is given proper weight. CQS also rates sources on a scale of zero to 100, but negative scores are not possible, unlike in CRI.

Though CQS has not been adopted as a standard yet, it is receiving much interest. The system is being used by many in the industry, says Yoshi Ohno, NIST Fellow, Sensor Science Division, who helped develop the scale. It is also under consideration by CIE technical committee TC 1-91, which is tasked with recommending color quality metrics.

The LRC recently proposed a certification of white light called Class A color. Intended as a communication tool for non-lighting professionals, the Class A designation is given to a source only after it has fulfilled four requirements: it has a CRI that is 80 or higher; the chromaticity must fall along a line of preferred tint, established through research; the chromaticity must fall within areas of roughly four-step MacAdam ellipses; and its gamut area index (GAI) should be between 80 and 100.

GAI, which measures color saturation or vividness, is derived from a light source's SPD and the same eight test colors that determine CRI. Calculations are done on a uniform CIE color space to produce chromaticity coordinates that form a polygon. The enclosed area is the gamut area. A larger area generally means a higher index and more saturated colors. Unlike CRI, GAI is not a fidelity metric, and an index greater than 100 is possible.

For the specification community, the LRC's Rea recommends GAI as a secondary metric to CRI. Research has shown it can influence light source preference. In tests, neodymium lamps, which have a lower CRI than incandescents but a higher GAI, tend to fare better in color rendering. For retail applications, LED products with a GAI of 130 or more can enhance merchandise's appeal by making colors "really pop," Intemax's Carey says.

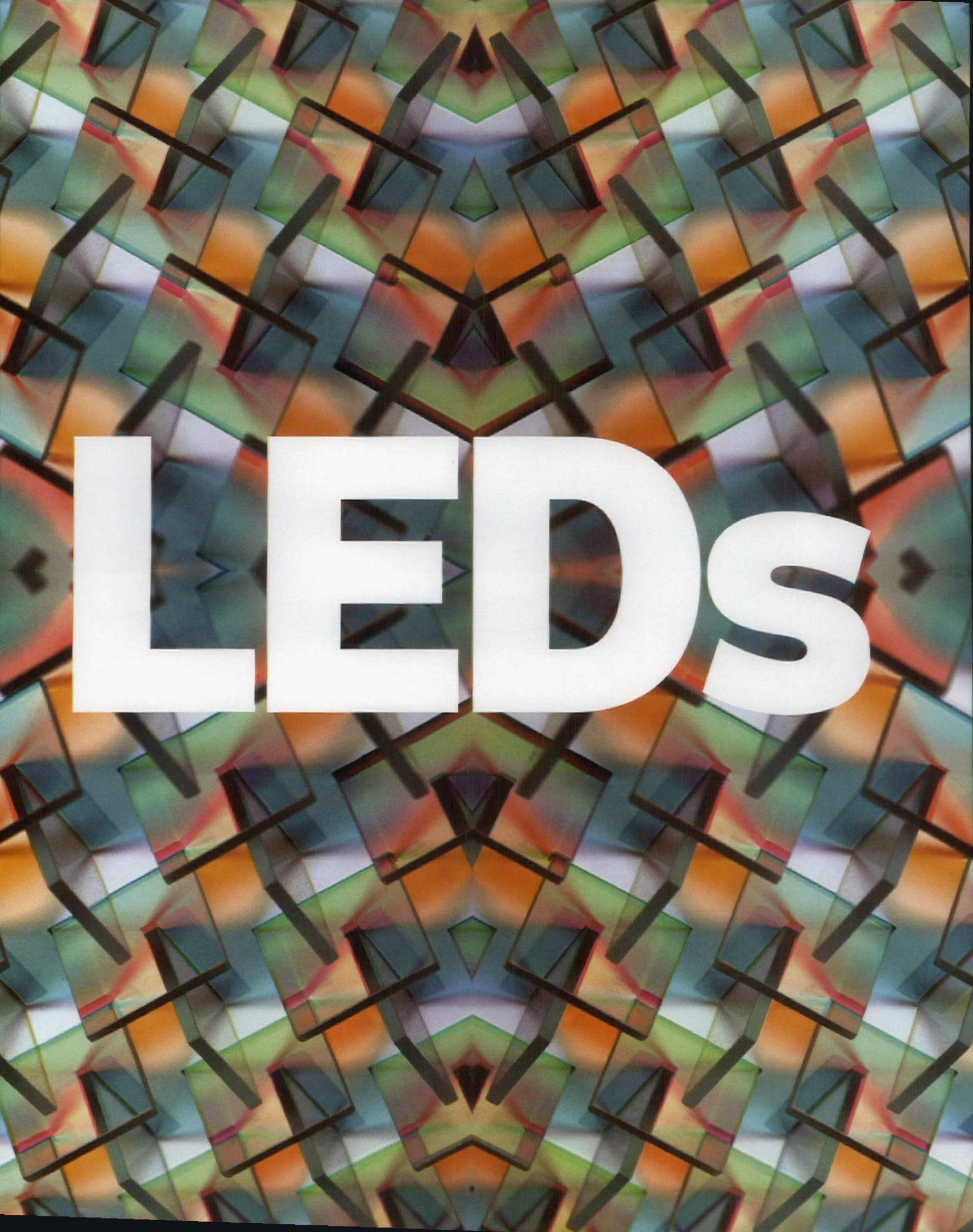
### ONGOING EFFORTS

The IES Color Metrics Task Group plans to finalize work on new color metrics this fall, after which they will undergo several rounds of approval by the Color Committee, Technical Review Council, and the Board of Directors, the PNNL's Royer says. The effort, which Royer is chairing, will incorporate aspects of CQS and have both a fidelity metric and a gamut area metric. Fifteen new test colors—different from R1 to R15—will cover a full range of hues and saturations, and the calculation methods and color spaces will be updated.

In addition to TC 1-91, the CIE has created a technical committee, TC 1-90, to develop a fidelity index to replace CRI. The CIE is also contemplating an update to its color-matching functions. Direct measurement of spectral cone sensitivities has revealed inaccuracies in the color matching functions (CMFs)—which determine a source's chromaticity coordinates—especially in the blue region. This "has significant ramifications for the LED industry," Xicato's Patil says. With blue diodes as the starting point for phosphor-converted LEDs, rectifying CMF shortcomings may lead to more accurate assessments of LED color performance.

The accuracy of an index, no matter how great, should never replace an actual mock-up of a light source. The degree of color rendering and white light needed is specific to the particular application. However, metrics that keep apace with LED technology can help lighting designers to better bridge the gap between measured color and perceived color. •

Lighting Resource Center


LEDs

TECHNOLOGY

# UNDERSTANDING OPTICAL PERFORMANCE

**Solid-state lighting can offer unparalleled performance if accompanied by the right lenses and reflectors.**

text by Alice Liao
art by Chris Wood

**Even the most efficient** light sources would be rendered useless without high-quality optics. A compact fluorescent lamp, for example, can lose up to 70 percent of its light if paired with an inappropriate optic, says Nadarajah Narendran, director of research at the Lighting Research Center (LRC), in Troy, N.Y. Likewise, the touted efficacy of LEDs wouldn't exist without the right optics.

Designing lenses and reflectors for solid-state lighting requires more than scaling them down from legacy sources. Yes, LEDs have smaller form factors than their conventional counterparts, but they differ in how they emit light. Incandescents illuminate in 360 degrees but LEDs are directional, illuminating only 180 degrees. This stems from the design of an LED package, typically comprising: one or more semiconductor chips, or die, mounted atop heat-conducting material; a primary optic—a lens or encapsulant—that encloses the die; and components to regulate heat and power. When current is applied, the chips produce light through electroluminescence.

Conventional lamps emit light via radiance or fluorescence. The source is surrounded by glass, metal, and acrylic reflectors that capture the omnidirectional light, guide it into the specified distribution, and work with lenses and optical accessories, such as louvers and baffles, to further shape the beam.

Although the output from LEDs is more concentrated, the distribution is too broad for most applications, and the light lacks intensity over distance. Therefore, LED lamps and fixtures typically incorporate one or more secondary optics, which can consist of lenses, reflectors, total internal reflection (TIR) optics (a lens and a reflector), and diffusers that collect the light, magnify its intensity, direct it to a target surface, and then blur it to enhance beam and color uniformity.

Choosing the appropriate optic depends on the application. Reflectors and TIR optics, which are common in LED MR16s and directional lighting, both have their advantages and disadvantages, says Frank Shum, vice president of LED products for Soraa.

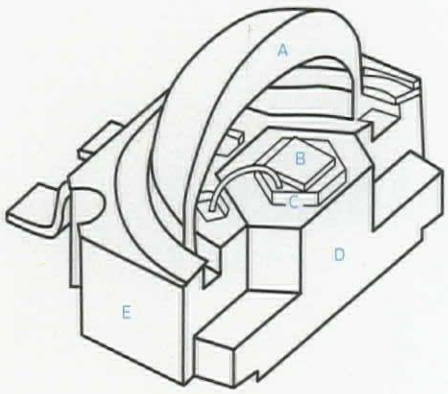
### REFLECTORS

Reflectors are simpler to implement and less expensive to manufacture than TIR optics. How well they collimate light—or propagate light into parallel rays—depends, in part, on their shape. Faceting or segmenting the surface can improve beam uniformity, as can applying different textures or finishes. If needed, lenses can further diffuse the light.

But reflectors don't solve everything. Light from an LED can evade parabolic reflectors, for example, and become spill light or, worse, glare. Moreover, many reflectors are vapor-coated with aluminum, a conductive material that can cause electrical shorting. Manufacturers can separate the reflector and LED circuit board with an insulating material, but the farther an LED package is to the reflector's input aperture, the less a reflector can "capture as much of the light as possible and re-direct it," says Catherine Leatherdale, product development specialist at 3M.

New specular films, such as 3M's recently introduced D50 series, are closing that gap. Made from polymeric material, these films can be applied onto a plastic substrate and are non-conductive, highly reflective, and, in some cases, optically superior to aluminum. Alternatively,

## Typical LED Package




A. Lens (primary optic)
B. Chip (or die)
C. Bonding substrate
D. Heat sink
E. Outer package

a specular polymer can be custom molded into reflectors to control the light precisely, enhance surface reflectance, and sit close to the LED.

**TIR OPTICS**

Designed around the phenomenon where light traveling from one medium to another of lesser optical density hits the interface at an angle and reflects with 100 percent of the beam energy, TIR optics, or TIR lenses, consist of a refractive lens nestled inside a reflector and are typically cone-shaped with optical efficiencies as high as 92 percent. The lens directs light from the source's center to the reflector, which sends it out in a controlled beam. An additional surface over the assembly provides another opportunity to modify the light.

Generally injection-molded from polymers, TIR optics are sculpted to a precise beam pattern with a variety of surface treatments—such as rippling, pillowing, or polishing—to diffuse the light, widen the beam spread, or shape distribution. Injection molding, however, limits lens size and wall thickness, typically to 0.5 inch. The larger the optics, the greater the risk of shrinkage and distortion. Maintaining a higher temperature and pressure on the machines for a longer time period can reduce the risk, Shum says, but at a cost.

TIR optics capitalize on characteristics unique to LEDs. Unlike incandescents, which radiate heat outward, LEDs send heat out their base, allowing TIR optics to fit snugly over their domed top. As a result, says Chris Bailey, director of the Lighting Solutions Center at Hubbell Lighting, "LEDs afford an opportunity for the designer to extract light directly from the source and precisely direct it through key vertical and horizontal planes."

Though prevalent in outdoor and industrial lighting, TIR optics are still gaining in indoor applications. While ideal for beam control, they don't work for all applications, Bailey says. For example, coupling is not necessary in architectural recessed lighting, where the emphasis is on diffused illumination, low glare, and a gradient distribution.

**SIZE MATTERS**

Shum says that the size ratio of an LED or LED package to an optic determines the beam angle. That is, narrower beams require smaller light sources or larger optics. Choosing the former affects output while choosing the latter can stress the limits of injection molding or system design if the lamp is small, as in the case of an MR16.

However, source sizes are increasing, driven by a need for higher luminous flux and convenience. To attract fixture designers to their products, LED manufacturers have introduced modular, high-output, chip-on-board (COB) LED arrays, which are becoming more common and can output 600 to 20,000 lumens at 6W to 200W, Bailey says. COB LEDs consist of multiple die that are wired to operate as one electrical device and assembled onto a ceramic package with a single emitting surface. Designed to produce a specific color temperature and lumen output, they take the guesswork out of creating a well-integrated LED.

But controlling the output from COB LEDs is more difficult. Their size increases the cost of injection molding the appropriate optics, and their flat surface does not lend well to coupling, which is key to the efficiency of TIR optics. Consequently, COB arrays fare better in applications where beam control is less critical, such as wide-distribution floodlighting or downlighting, Bailey says. But their optical and electrical needs are also simpler. Typically, one optic is sufficient and "electrical connections can be made using simple plug-and-play," he says.

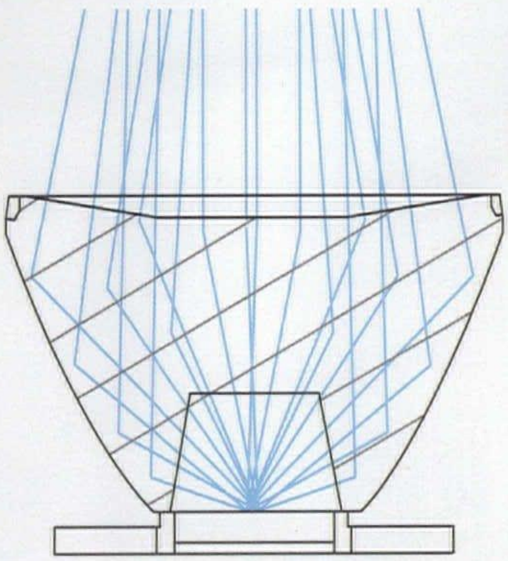
High-flux density (HFD) LEDs are also growing in popularity. They also consist of multiple die, but each is smaller than those in a COB array and can handle more current, Bailey says. The result is more light output from a smaller lighting-emitting surface. The die are in a domed surface, which easily accommodates a TIR optic and therefore offers more output control. These high-powered LEDs come in 4W to 60W and output anywhere from 400 to 6,000 lumens, Bailey says.

**NEW CHOICES**

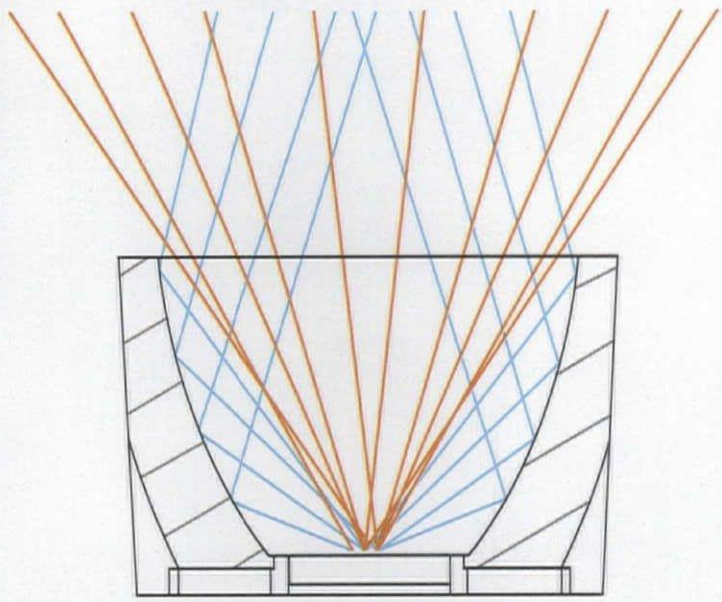
Although the laws of physics have limited the availability of small LED lamps with tight beam angles, progress is being made. Soraa's Point Source Optics, which features a folded prismatic optic designed by Shum, led to the company's LED MR16 lamp with a 10-degree beam spread. The folded optic reflects the light emitted from a single LED package multiple times before propagating it out, and blurs the light near the beam's central axis—as opposed to its outer edges—creating a smooth, well-defined beam. Shum says this larger diameter optic can be injection molded because its diameter to height ratio is 6:1, whereas typical TIR optics have a ratio of 1.25:1. The Soraa Snap System allows users to magnetically snap a variety of lenses and optical accessories to the MR16 and shape, widen, or narrow the beam and eliminate glare.

Also tackling the issue of source size, Reading, Mass.–based Fraen Corp. has developed a multi-TIR nested lens for use with any COB LED product to create a narrow beam spread. Though the larger footprint of the COB LED would typically require a proportionally larger optic to fully control its illumination, the compact nested lens design

Total internal reflection (TIR) lens



Legacy reflector



produces a collimated beam with little spill light. And, of course, a smaller optic means a smaller luminaire.

**TAKING THE HEAT**

The increasing lumen output of COB and HFD LEDs also means more heat. As these sources become more common, proper thermal management will become more critical in ensuring the performance and life of a diode, as well as the fixture's circuitry. In fact, because of the increased heat, LEDs today are encapsulated with silicone instead of epoxy, which was used in the early days of LEDs when outputs were measured in milliwatts. Epoxy degrades above 80 C, whereas silicone can withstand temperatures of up to 200 C, Narendran says.

While coupling can improve optical efficiency, exposure to heat and light—particularly from the high-energy blue portion of the spectrum—can cause the materials to degrade over time. Lenses and reflectors can yellow, leading to color shifting and performance discrepancies between fixtures, Narendran says. A uniform lighting design on day one may "start producing different colors, which, in turn, will affect the aesthetics of the space," he says. Hazing can also occur, reducing the optics's ability to direct the lumen output.

Not surprisingly, heat-resistant materials are garnering interest from LED optics and fixture makers. One material of choice for TIR optics is PMMA (polymethyl methacrylate) acrylic, favored for its clarity, UV stability, and high transmissivity, Hubbell Lighting's Bailey says. However, long-term heat exposure may cause deformations.

Manufacturers have also turned to glass, which, Narendran says, "is a good candidate because it's much more robust than polymers." It also offers high transmission, but can be heavy, fragile, and expensive to manufacture.

Polycarbonates that address the specific needs of LEDs are another strong contender. Bayer MaterialScience's Makrolon LED-grade materials are designed to tolerate long-term heat exposure, transmit light effectively, and have good clarity. A diffusion additive can also be added to polycarbonates to mitigate glare.

As manufacturers continue to explore the opportunities unique to LEDs, the push for higher efficacies will introduce new heat-resistant materials and more customized optical solutions. According to Marco de Visser, manager of marketing communications for Dutch 3D printed optics maker Luxexcel, the latter has already begun; 3D printing technology is speeding up prototyping and printing optics to order. Such developments will further emphasize solid-state lighting's importance as a source of not only efficiency but also beautiful and controlled light. •

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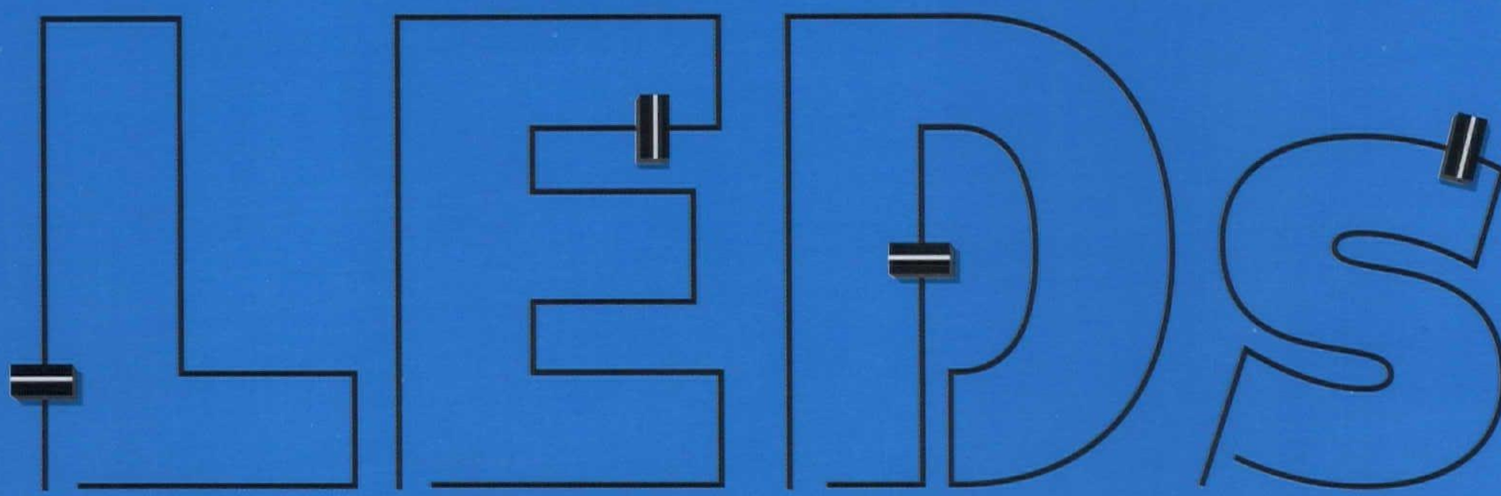



TECHNOLOGY

# TAKING CONTROL

## The digital nature of solid-state lighting frees designers from wired connections.

text and diagrams by
Dan Weissman

**Amid today's golden age** of digital technology, new developments in lighting control systems allow for smarter data input, conversion, and application than ever before. Until we achieve fully controllable wireless lighting, manufacturers are competing to integrate the capabilities of solid-state lighting with existing systems, protocols, and installation methods. Understanding the components of control systems, how they interact, and how to represent control concepts is key to project delivery.

Any lighting control system can be reduced to a few elements: input electricity; input data, such as an on–off signal from a switch or sensor; data-to-information converter, such as a computer chip that translates daylight sensor data into a dimming signal; information transmission through wires or wireless signals; and information output in the form of visible light from a source.

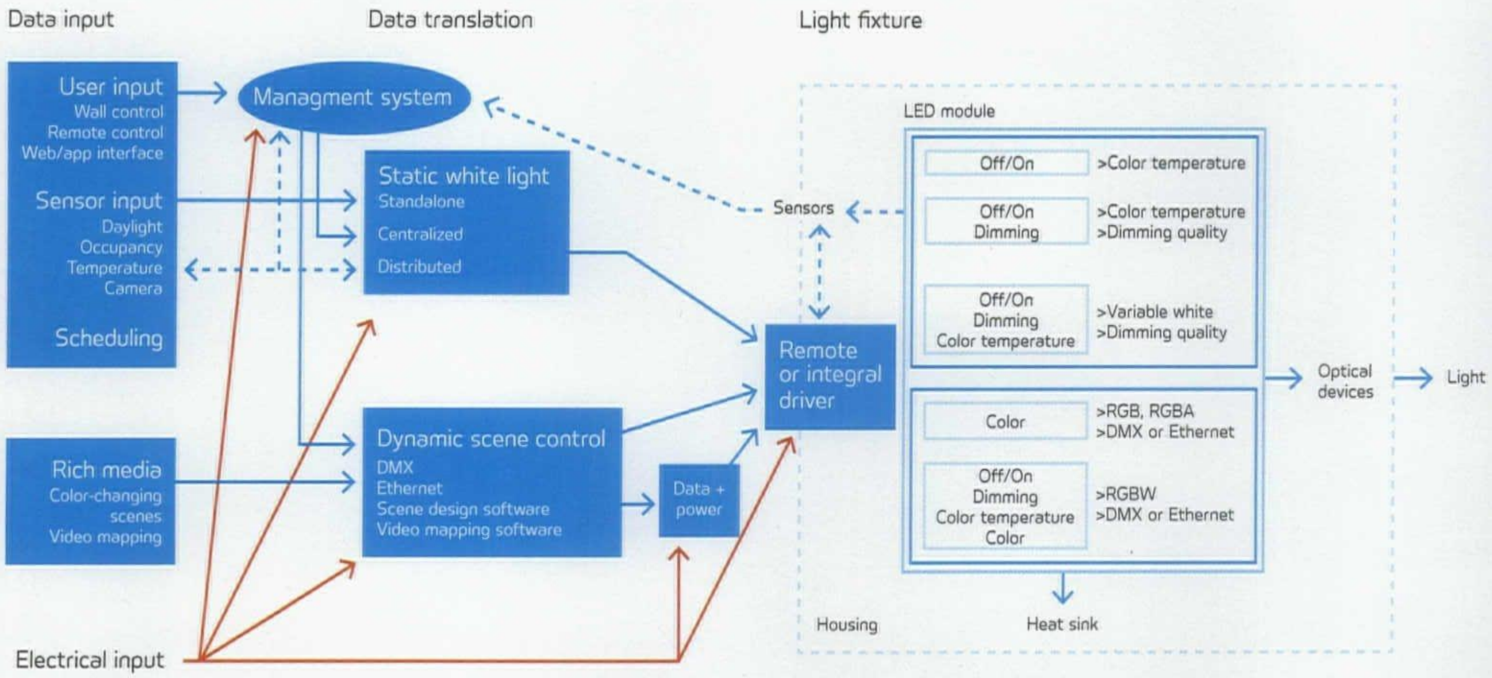
Prior to the development of digital control systems, physical wires had to be snaked from each fixture to a centralized control center. Transformers and dimmers, which required large coils of copper housed in metal boxes with heat-dissipating fins, needed to be located in designated fireproof spaces. To provide the desired control of electric light, these systems drew an immense amount of energy and physical resources. Though contemporary systems may still incorporate elements from these legacy systems, the days of their reliance are numbered as wireless and digitally addressable systems mature.

### DATA IN, INFORMATION OUT

The terms data and information are often used interchangeably, but they have distinct meanings when describing a control system: Data entering the system is processed, and the resulting information learned from the data is what controls luminaires. Although both electricity and data flow through any lighting system, this article will focus on how control systems make this data-to-information transformation possible.

Knowing when to turn on, turn off, or dim a source requires information that enters a control system as data at an input device. Any given light fixture is limited in control by the

## General Lighting Control Diagram




types of information it can accept. Whereas legacy sources only allowed switching or dimming, solid-state light sources allow up to four control variables, depending on the driver and LED specifications: switching, dimming, color temperature, and color.

Furthermore, nuances for each exist: Lights may dim to 10 percent, 5 percent, or 1 percent output before switching off; color may be created with RGB (red, green, blue), integrate amber for richer colors, or even include white LEDs for nicer white light distinct from color-changing capabilities. These options are available not only because the physically small nature of LEDs allows many diodes to fit within a fixture, but also because of the new capabilities of digital controls.

Today, digital systems may handle a diverse array of sensor data such as photocells and occupancy sensors, visible-light or infrared cameras, and geofencing technologies, all able to gather data from the environment. Building and energy codes, which once only acknowledged connected loads, now include requirements for automatic controls to limit electric lighting usage when not needed.

Brent Protzman, manager of energy information and analytics at Lutron, notes that ANSI/ASHRAE/IES Standard 90.1–2010, the 2012 International Energy Conservation Code, and California's 2013 Title 24 energy standards all now require occupancy sensing as well as multilevel light control and daylight controls in certain spaces, such as open offices. Sensors may be standalone pieces of hardware or integrated into the light source itself.

The digital nature of LEDs allows easy integration of onboard sensors that can speak to the driver and control the light source, or provide feedback data to a larger control system. While onboard control sensors were originally developed in fluorescent fixtures, digital protocols have allowed a much finer degree of control and flexibility, and decreased physical size of components. For example, many LED streetlights now have a computer chip programmed with scheduling data that lowers lumen output when traffic dies down after evening rush hours to save energy and prolong fixture lifetime. The chip may also talk to adjacent fixtures, creating a mesh network that feeds data back to management controls. A distributed network where each fixture has its own controls is inherently more robust than a centralized system, particularly in outdoor environments, since each fixture is an independent, self-operating entity.

Sensors integrated into LED fixtures can also provide feedback about the life and health of the driver and source, or serve as node points for other environmental sensors such as motion, temperature, or illumination. Retail and other commercial spaces have begun integrating location-tracking technologies, such as that by GE Lighting and ByteLight, into light fixtures. Whereas the vacuum of the A-lamp once helped us see, these digital sources now see us.

### DATA CONVERSION AND TRANSMISSION

At the heart of any control system are components, devices, and software that convert complex input data signals into language that light sources understand: switching and dimming. A photocell can only report light levels; it can't decide when to dim the luminaires or when to warm the color temperature by dimming down blue diodes and turning up reds.

These conversion elements form the backend of a control system and comprise circuit boards, data compiler boxes, relay panels, and fixture drivers. In replacement LED lamps, data conversion may occur within accompanying mobile apps, base stations, or the lamp enclosure itself. In larger installations, centralized controls may operate over entire buildings or campuses, using any number of protocols and control hardware.

Cutting-edge building management systems from companies such as CommScope, Lutron, and Schneider Electric all include various data input options, control settings, and feedback data analysis capabilities. These systems promise a Rosetta Stone, translating data inputs from users, building sensors, light sources, HVAC, and other connected building systems into a smart learning machine that can tune the building by modifying daylighting controls or adapting schedule settings based on occupant-use patterns to minimize energy use.

Where legacy control systems require a home-run connection and command station, networked digital controls are distributed and may not require a center at all. Europe and much of the rest of the world have adopted DALI (Digital Addressable Lighting Interface) as a standardized networked protocol. The U.S. has seen far fewer DALI installations to date; instead, we rely on proprietary digital systems by manufacturers or open protocol systems.

Regardless of platform, these control systems allow fixtures to be powered from any available source, data wired in series (or controlled wirelessly), and then digitally addressed on the system after installation. Fixtures may then be zoned—or grouped with other fixtures for particular lighting presets—or configured into scenes, irrespective of installation location and wired connections, enabling spatial flexibility, local control provided to designated fixtures, and assignment of pre-set levels to each fixture. Master control through a computer interface can then be accessed via any wired or mobile device on the system.

### DYNAMIC LIGHTING, DYNAMIC CONTROLS

Arguably the most visible development in LED lighting is the ability to address nodes, which allows designers to create dynamic scenes in white light or color. Although some manufacturer literature uses "node" to reference the point at which data and power are combined and fed to multiple fixtures, this article uses the term to mean individual pixels in a system.

Digital multiplex (DMX), the industry standard for theatrical lighting control since the 1980s, was designed for use with a theatrical dimming board. Today, it is the most widely used data protocol, or digital lighting controls language, for dynamic architectural lighting. DMX has two units of measure: the channel and the universe. While a single channel is analogous to a single dimmable circuit in a conventional system, one universe of DMX supports 512 channels. In an RGB color-changing node, each channel represents one color of light, or three channels. A quick calculation reveals that 170 nodes of RGB (totaling 510 channels) can be controlled by one DMX universe, and large systems can contain multiple universes.

Manufacturers of architectural color-changing systems have evolved away from the theatrical board. Instead, they have developed control boxes of various sizes that receive scene data from a flash drive, computer, or Web interface and send out DMX signals to fixtures. Design and control software, often provided by the manufacturers, may be used to develop scenes from standard templates or map video input onto a grid of nodes. (But just say "no" to the default rainbow-fade setting.)

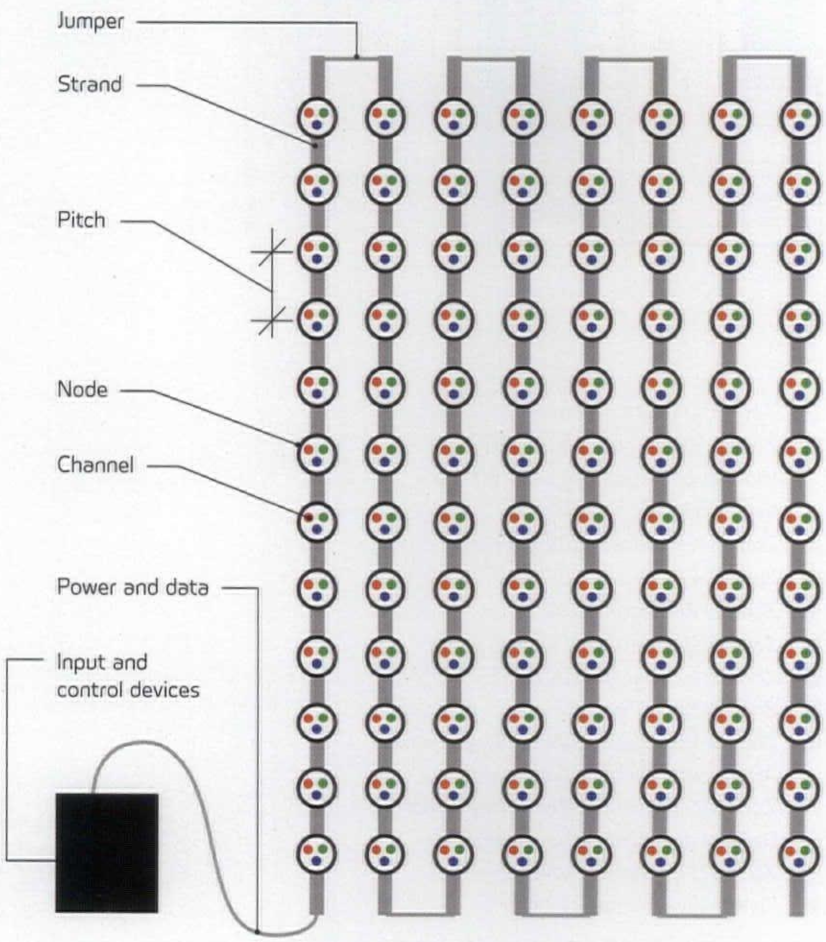
For all its ubiquity, DMX is still limited when handling large installations. Increasingly complex setups use direct Ethernet connections and computer management to populate pixels more akin to a monitor than theatrical lighting.

### CONNECTING DEVICES AND PEOPLE

For the foreseeable future, electricity will continue to flow through copper wires from power sources to fixtures. However, control data can travel through many media: optical fiber, CAT 5 cable, or wireless signals. Lutron's Protzman says his company's wireless controls are increasingly used in commercial and retrofit applications because of the cost savings that come from the reduction in cable material and installation time.

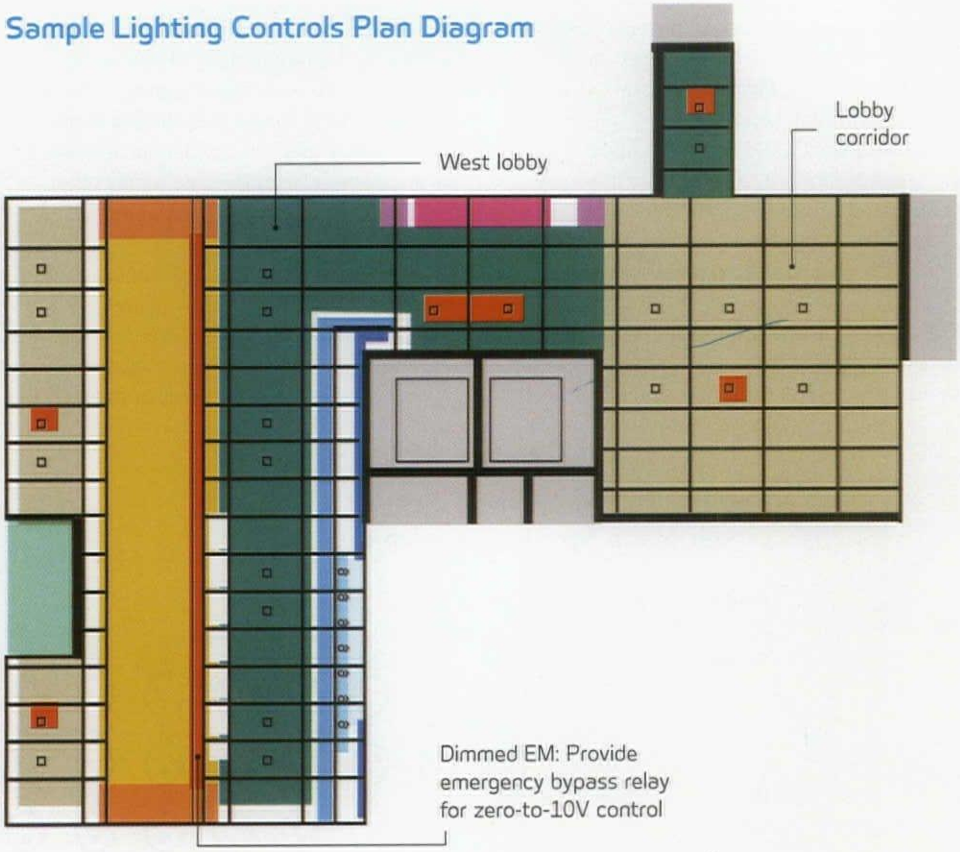
As ambient computing and the Internet of Things find homes in our built environments, organizations such as ZigBee Alliance and EnOcean Alliance have developed alternate standards to ensure interoperability across

## Sample Media Façade
## Linear Node Strand Diagram with LEDs




A media display is an array of nodes—individual pixels that may be white light only or RGB, and include multiple diodes and accessories—that creates dynamic scenes or lighting effects. LED nodes are connected to a strand of sheathed wiring for data and power; standard pitches, or spacings between nodes, are 4 inches, 6 inches, and 12 inches. The input and control devices utilized will depend on a project's requirements and content. Applications with integrated media displays that employ a few scenes may need only a small box with self-contained control hardware, while video displays may also require an encoder and converter. The control device, which supplies power and data to the media display, will typically use the control protocol DMX, or digital multiplex that can operate 512 channels—communication lines between the control device and source—per universe. DMX technology allows jumpers to daisy-chain multiple strands of nodes together.

## Sample Lighting Controls Plan Diagram




- Zone 1: Daylight switching
- Zone 2: Downlights and washlights. (Normal operation: Full on. After hours: See EM plan.)
- Zone 3: L1 [zero-to-10V dim]
- Zone 4: L1 [zero-to-10V dim]
- Zone 5: R8 [zero-to-10V dim]
- Zone 6: G1 [zero-to-10V dim]
- Zone 7: L2 [zero-to-10V dim]
- Zone 8: Backlit wall
- Zone 9: L6 Display Lighting (Daytime: On. After hours: Client to determine.)
- Zone 10: R5 fixtures (Normal operation: Daylight switching. After hours: On.)
- Zone 11: L3 Vertical coves
- Fixtures on emergency circuit

hardware. ZigBee, according to chairman and CEO Tobin Richardson, lobbies manufacturers to develop all types of products with the Institute of Electrical and Electronics Engineers (IEEE) 802.15 standard for mesh-networking, which operates at lower power than the IEEE 802.11 standard, which Wi-Fi uses, and avoids potential conflicts with computers and mobile devices.

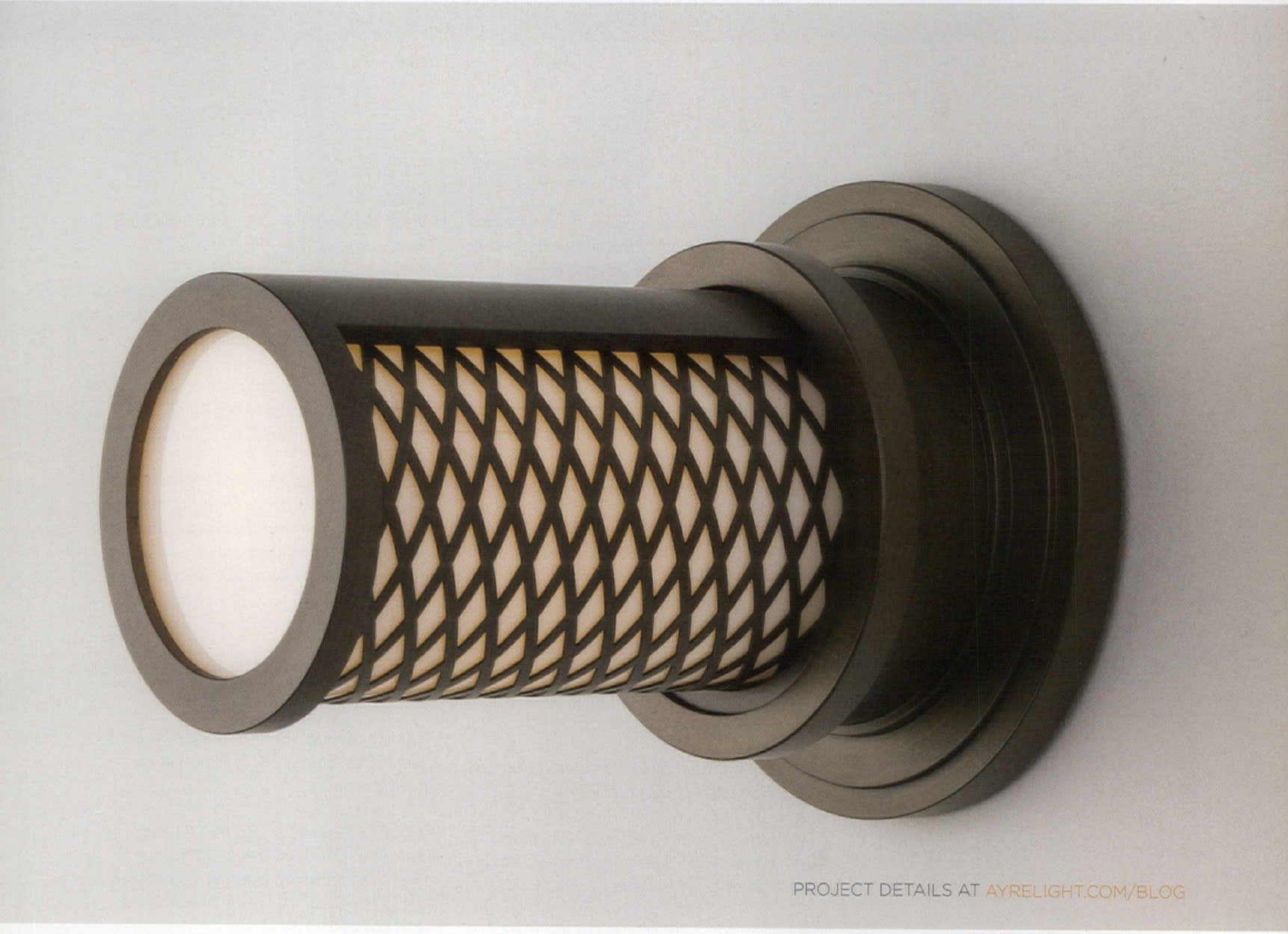
Meanwhile, EnOcean lobbies manufacturers, specifically in the building industry, to adopt a technology produced by its namesake German manufacturer, which transmits low-powered data signals by harvesting energy from micro-movements present in all physical objects. Regardless of protocol, electrical things in our buildings will soon talk to each other, suggesting opportunities we haven't even imagined.

Building-scaled lighting control systems now offer many bells and whistles, and technologies across multiple manufacturers only add complexity. Communication among project stakeholders is critical to implementing robust systems that may take advantage of opportunities offered by LED technologies. However, because lighting control is no longer limited by physical wired connections, engineering wiring diagrams now do little to represent control concepts.

To that end, lighting controls diagrams developed by the lighting designer, architect, or interior designer serve to aggregate the spatial information in a wiring diagram with temporal information in a controls narrative and scene schedule. Such diagrams provide design, engineering, and construction teams, as well as the owner or facility manager, with an overview of a control system's intent, including which fixtures should operate together, when and how scenes change, and the locations of automatic and dynamic controls.

Soon enough, all building lighting will be completely wireless, fully networked, sensored, and seamlessly controllable via Web or mobile apps. In the meantime, smart integration with existing systems is critical to transitioning building projects, which will continue to require multiple types of control for various design elements throughout the building. The options are plentiful, but, in the end, most lighting control scenarios still boil down to the basic questions. When should the lights be turned on? How bright? When should they be turned off? What is their purpose? Ultimately, what we seek are integrated systems that provide the light we need at the times we need it, monitor and minimize energy use, and entertain us when the moment is right. •

*Dan Weissman is director of Lam Labs at Lam Partners, in Cambridge, Mass.*


PROJECT DETAILS AT AYRELIGHT.COM/BLOG

# ·RESOURCES

An introductory list of articles that discuss the topics of and issues related to flicker, dimming, color, optics, and controls as they pertain to solid-state lighting.


### FLICKER

*ASSIST Recommends ... Flicker Parameters for Reducing Stroboscopic Effects from Solid-State Lighting Systems*, by the Alliance for Solid-State Illumination Systems and Technologies and the Lighting Research Center, May 2012. Available at *bit.ly/Q84AvS*

"Flicker happens. But does it have to?" by Cree, 2013. Available under white papers at *bit.ly/1iUBg5U*

"Exploring flicker in Solid State Lighting: What you might find, and how to deal with it," by Michael Poplawski and Naomi Miller, Pacific Northwest National Laboratory, 2011. Available at *bit.ly/1hgwlrH*

*Dimming LEDs with Phase-Cut Dimmers: The Specifier's Process for Maximizing Success*, ibid., October 2013. Available at *1.usa.gov/Q84Fzu*

### DIMMING

"Controlling LEDs," by Lutron Electronics Co., 2011. Available at *bit.ly/1kFPBlt*

"The Subtle Circuitry Behind LED Lighting," by Bernie Weir, IEEE Spectrum, Feb. 27, 2012. Available at *bit.ly/1nZxsEs*

"Dimming LEDs with Phase-Cut Dimmers: The Specifier's Process for Maximizing Success," by Naomi Miller and Michael Poplawski, Pacific Northwest National Laboratory, 2013. Available at *1.usa.gov/1g3cGfs*

*ASSIST Recommends ... Dimming: A Technology-Neutral Definition*, by the Alliance for Solid-State Illumination Systems and Technologies and the Lighting Research Center, April 2013. Available at *bit.ly/1fMM8EA*

*LED Lighting Facts*, by the U.S. Department of Energy, 2014. Available at *lightingfacts.com*

### COLOR

*Value Metrics for Better Lighting*, by Mark S. Rea, published by SPIE Press, 2013

"LED Color Mixing: Basics and Background," by Cree, 2014. Available at: *cree.com/xlamp_app_notes/color_mixing*

"Defining the Color Characteristics of White LEDs," by Steven Keeping, April 23, 2013. Available at Digi-Key Corp.: *bit.ly/1qArLLo*

"LED Color Characteristics," by the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, Building Technologies Program, January 2012. Available at: *1.usa.gov/1lO7AWI*

### OPTICS

*TIR Lens Guide*, by LEDiL, 2012. Available at: *bit.ly/LEDiLTIR*

"Quality of Light: Perfect Spectrum, Perfect Beam," by Soraa, 2013. Available at: *bit.ly/1tpsmDb*

*CALiPER Report 22: LED MR16 Lamps*, by the DOE, Office of Energy Efficiency & Renewable Energy, Building Technologies Program, Sept. 14, 2014. Available at: *1.usa.gov/YYwvTm*

*Secondary Optics Design Considerations for SuperFlux LEDs*, by Lumileds Lighting, 2002. Available at: *bit.ly/1mgWgZB*

### CONTROLS

"Controlling LEDs," by Lutron (Ethan Biery, Thomas Shearer, Roland Ledyard, Dan Perkins, Manny Feris), May 2014. Available at: *bit.ly/1kFPBlt*

"Maximizing energy savings with control over light," by Koninklijke Philips Electronics, April 2013. Available at: *bit.ly/1oHUth6*

*LED Lighting Explained*, by Jonathan Weinert, published by Philips Solid-State Lighting Solutions, 2009. Available at: *philips.to/1EyxFUL*


Lighting that goes where your imagination takes it.
Up a wall, across a ceiling, down to a pendant right in front of you. All in a single, clean line.