Solid-state lighting design requires a system-level approach

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There are many challenges to be faced in designing solid-state lighting fixtures using light-emitting diodes: the design team must consider the whole system rather than simply looking at individual components.

Mention the words ‘solid-state lighting’ and most of us will think of the latest advances in high-flux light-emitting diodes. In the space of a few short years, the semiconductor industry has gone from indicator lamps to devices that rival incandescent and fluorescent lamps in luminous efficacy. The promise of solid-state lighting (SSL) for general lighting applications is being fulfilled.

Look more closely, however, and there are still many challenges to face on the road from research lab to commercial production. High-flux LEDs are the equivalent of bare incandescent and fluorescent lamps. Many other issues in the systems must be addressed before affordable solid-state lighting fixtures (or ‘luminaires’) will be seen in our homes and offices.

Color and intensity
Most general lighting applications require ‘white’ light. This is currently produced by incandescent, fluorescent, and high-intensity discharge (HID) lamps. There are two approaches to generating white light with LEDs: phosphor-coated LEDs and multicolor LED assemblies.

Phosphor-coated LEDs (pcLEDs) consist of blue LED dies that are coated with rare-earth phosphors. These absorb a portion of the blue light and re-emit it as yellow. The combination of the blue and yellow produces cool white light. By adding red-emitting phosphors, warm white light can also be produced. Multicolor LED assemblies consist of separate red, green, blue (RGB) and sometimes amber (RGBA) LED dies mounted on a common substrate. Thorough mixing of the colored light from these LEDs again produces white. Unlike pcLEDs, however, the proportion of each color can be varied to produce a white light source with an adjustable color temperature.

The challenge facing the luminaire manufacturer is that the bin code of color LED dies is currently based on dominant wavelength (i.e., color) and intensity. Phosphor-coated LEDs are similarly binned by intensity and chromaticity. This makes it difficult to maintain product consistency without resorting to single bins. Further improvements in semiconductor or phosphor technologies should enable LED manufacturers to produce LED dies with tightly-controlled dominant-wavelength intensity and chromaticity characteristics. Until then, luminaire manufacturers will continue to struggle to maintain product consistency in terms of color and intensity.

Color rendering
Incandescent lamps and daylight, by reason of their broad spectral content, have good color-rendering capabilities, while mercury-vapor discharge lamps, with their prominent line spectra, are generally poor. Phosphor-coated LEDs and RGB LED assemblies tend to have acceptable color-rendering capabilities, but there is room for improvement. The addition of red-emitting phosphors to pcLEDs and amber LEDs to multicolor LED assemblies offer improvements, but at additional cost.

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The lighting industry currently relies on the CIE colour rendering index (CRI) as a metric for ranking the color rendering abilities of white light sources, including white-light LEDs. Unfortunately, this metric was developed in the 1960s for fluorescent lamps, and is ill-suited to solid-state lighting. However, an improved metric has recently been proposed by NIST, and the subject is currently being reviewed by the CIE.

LEDs as point sources
From an optical-design perspective, LEDs are effectively point light sources. It is much easier to design LED-based luminaires that are small and aesthetically pleasing than it is incandescent and fluorescent lamps. The design process is further simplified by LED packages with integrated optics that offer beam patterns from narrow spots to wide floods and batwing distributions. The current generation of high-flux LEDs use molded epoxy and acrylic lenses, but diffractive micro-optics offer design advantages.

The fact that LEDs are point sources can also be a disadvantage, however. The extreme luminance of high-flux LEDs can result in glare if the lights are viewed directly. In addition, color fringing of shadows can occur if the light from multicolor LED modules is not sufficiently mixed. Frosted glass and plastic diffusers commonly used in luminaire design are applicable to LED-based designs, but holographic and deterministic diffusers offer improved transmittance and better optical control.

Thermal issues are critical
Heat dissipation remains one of the critical issues for LED-based luminaire design. The luminous efficacy of LED dies decreases with increased junction temperature (Figure 2). As a worst-case example, the efficacy of amber LEDs decreases by 80% when the junction temperature increases from 25°C to 120°C. Worse, the mean time between failures (MTBF) of LED packages decreases by half for every 10°C increase in LED junction temperature over the manufacturer’s recommended maximum.

Maintaining reasonable junction temperatures can be a challenge, particularly for outdoor luminaires with sealed housings and ceiling-mounted luminaires with limited air circulation. Current designs feature massive aluminum heat sinks. These are obviously more expensive than the sheet metal constructions used for many architectural luminaires. Miniature heat pipes are useful in transporting the heat from the LED packages to remote heat sinks, but the heat sinks are still required.

The situation will improve as LED manufacturers increase the luminous efficacy of their products. This will reduce the thermal load of LED-based luminaires considerably, leading to smaller, less-expensive heat sinks.

Optical feedback
Luminaires with RGBA LED assemblies can offer independent control of intensity and chromaticity. This means that the luminaire can emulate an incandescent lamp by decreasing the color temperature as the luminaire is dimmed. It can also maintain a constant intensity as the user varies the color temperature from warm to cool white, or change both intensity and color temperature in response to changing daylight conditions.

Designing an optical feedback system for these features poses interesting design challenges. Firstly, the peak wavelength of LED emissions shifts with junction temperature, typically 0.4-0.9nm per degree Celsius. In addition, the spectral responsivity of the photosensors may change with ambient temperature. This makes it difficult to distinguish changes in intensity from changes in chromaticity.

Another challenge is that the feedback controller must have a response time of less than 50ms. If it is too slow, the luminaire will be perceived to flicker when the feedback controller responds to sudden changes in luminaire intensity. Worse, the dynamic range of the photosensor signals should be at least 14bits to accommodate the full range of intensity and color temperature changes. This pushes the performance of inexpensive microcontrollers to their limits.

As shown in Figure 2, the different temperature dependences of the LEDs must also be taken into account. Without an optical feedback system, the chromaticity shifts during dimming or changes in ambient temperature can be unacceptable.

Yet another issue is the need to reliably and unobtrusively sample light from the LED assemblies over a wide range of intensities and chromaticities while ignoring ambient light conditions. Innovative optical designs are still required to solve this problem.
Electrical considerations

LEDs are constant-current devices whose intensity can be controlled using analog or digital techniques. These include pulse-width and pulse-code modulation. The modulation rate must be at least 300Hz in order to avoid visual flicker. However, the thermal time constant of most LED dies is approximately 10ms. A modulation rate of at least 1000Hz is needed, therefore, to avoid undue thermal stressing of the wire bonds that may lead to premature device failure.

The response time and stability of the power supply feedback system is also important. Most commercial DC power supplies are designed for constant loads, and perform poorly with light or rapidly changing loads. In general, power supplies must be designed specifically for high-flux LED applications.

Lighting controls help reduce energy consumption

LED-based luminaires are potentially more efficient than the fluorescent luminaires used in today’s offices. It has been estimated that SSL can reduce the global consumption of energy for lighting by 50% by 2025. This does not, however, take into consideration energy savings provided by networked luminaires and ambient light sensors. Several studies of typical office buildings have shown that retrofitting fluorescent lighting systems with networked luminaires can result in energy savings of 60-85%.

Solid-state lighting offers many opportunities for intelligent luminaires that can communicate with occupancy sensors, daylight sensors and building management systems for peak load-shedding and scheduled operation. Unlike conventional luminaires, LED-based luminaires already have on-board electronics for managing AC/DC power conversion and optical feedback. Adding network communications is a simple task.

Finally, LEDs have response times of less than 100ns. This opens the possibility of using LED-based luminaires for illumination and optical communication within open office spaces.

Conclusion

There are many issues that must be considered when designing LED-based luminaires for general illumination. The design team must be familiar with optical, electrical, thermal, electronic and mechanical engineering, and be familiar with photometric and colorimetric measurement practices. Above all else, the team must view solid-state lighting as a complete system rather than the sum of its components.

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Ian Ashdown, Fellow IESNA, is senior research scientist for TIR Systems Ltd., Burnaby, BC. He has 30 years’ experience in lighting design, research and development, and software engineering. He is the author of numerous academic papers, magazine articles and book chapters on the technical aspects of illumination engineering and lighting design. For several years he has been involved in SPIE’s Solid State Lighting conference, as an invited speaker (SSL II), giving an oral presentation (SSL III) and as conference co-chair (SSL V).

References