Informational Document

Optoelectronic Products

LEDs for Lighting Applications: An Overview

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This white paper introduces the reader to the issues and advantages surrounding LED lighting and LED lighting design. Color concepts including CCT and CRI are covered with useful spectral information comparing various light sources. LED-based designs are analyzed from the standpoints of power management, heat management, and dimming. Innovative applications and benefits of LED-based sources conclude this paper.

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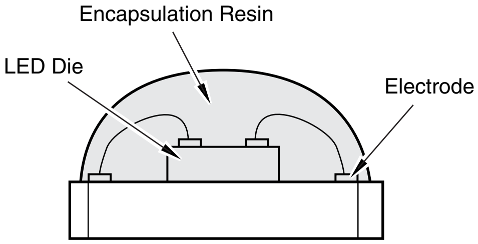
LEDs: An Introduction

A Light Emitting Diode (LED) is a semiconductor device that produces light when current is passed in one direction. Light is produced from the energy conversion that occurs in the LED structure, much like a tiny light bulb. However, due to their semiconductor-based structure, LED lights are much more rugged and damage resistant than ordinary light bulbs and fluorescent tubes.

When beginning to craft a luminaire, the choice of basic light source requires the consideration of many factors. LED technology is quickly advancing, as is the demand to integrate LEDs into more types of products. Methods for powering LEDs differ greatly from methods used in other types of lighting, so there are many important concepts and design considerations that must be understood.

There are many significant benefits to working with LEDs; energy conservation is one of the most widely known. A direct comparison of LEDs to other prevailing lighting technologies, such as incandescent and fluorescent, indicates the energy savings that can be realized. Incandescent light uses the most energy, fluorescent is second, and LEDs are the most efficient of the three.



LED Cross Section

Figure 1: Generic Lighting LED

Basic LED Lighting Concepts

Chromaticity

Chromaticity provides an objective value of the quality of a color without regard to luminance. Chromaticity is therefore determined by hue and depth of color (i.e., saturation and chroma).

LED Color Uniformity

In an LED (and especially with white LEDs that use phosphors to achieve their white color), color temperature can easily vary due to a number of factors. The variations can be visible to the human eye [Figure 2], even though the devices have the same Color Temperature (CCT) rating. Physical variations can include: phosphor composition from batch to batch, fixture materials, operating junction temperature, forward current, fixture or cover materials (if used), heatsink design, and manufacturing quality. Electrically, the LED's color temperature in pulsed applications can be affected by its forward current and duty cycle.

To identify variances and ensure consistency within a specific set of devices, LEDs are "binned," or sorted, during manufacturing into sub-groups with similar color coordinates. Binning defines an LED's spectrum via a set of X and Y chromaticity coordinates. The "tightness" of these specifications' color measurement varies by vendor.

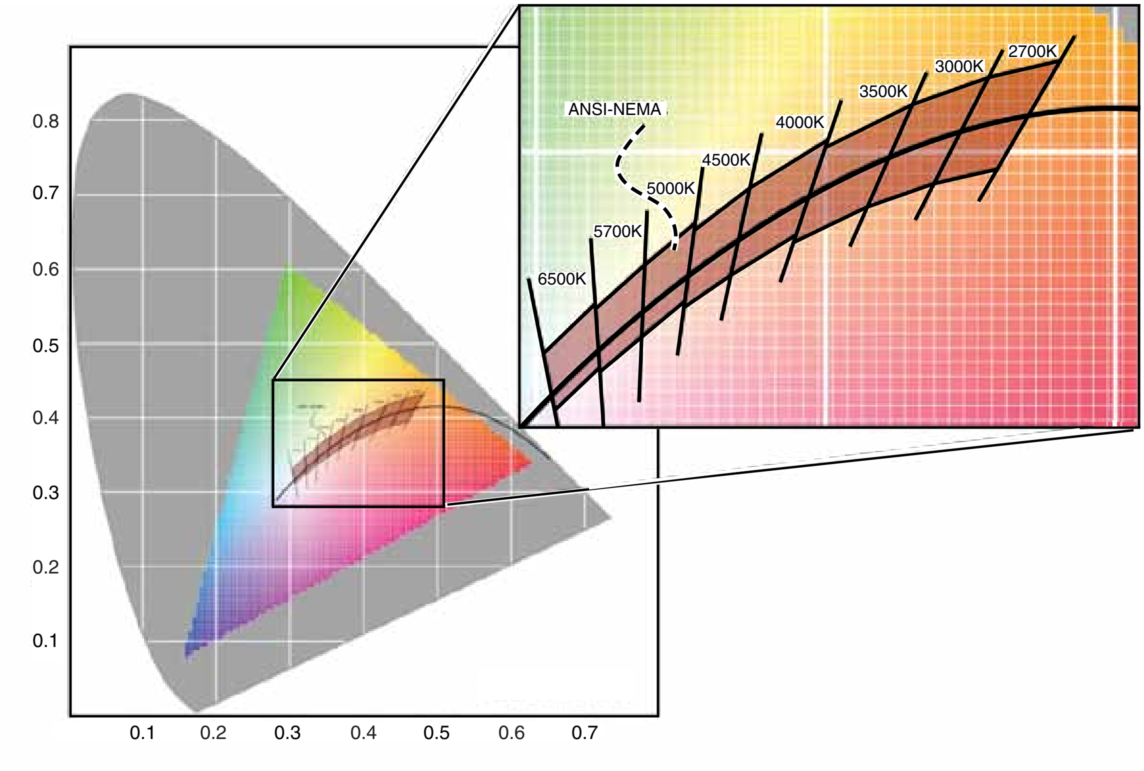


Figure 2: LED color Uniformity: This curve is based on the Macadam Ellipse which shows the human eye's ability to see a change in color. The dark curve is a Black Body Curve which is temperature dependent. The ANSI binning follows the Black Body Curve and shows the possible variations for color temperature (industry standard color bins are shown).

Luminous Efficacy

Luminous efficacy is a description of how well a light source can provide visible light from a given amount of energy. A comparison of the luminous efficacy of common lighting types would show that fluorescent light is better than incandescent, and an LED light source is better still.

Luminous Flux

Luminous flux provides a measurement for the perceived power of light. Very different from radiant flux, which shows the total power of light emitted, luminous flux is adjusted to the various wavelengths of light as perceived by the human eye.

Luminous flux can be used as an objective measurement of “useful” power (i.e., that which creates light the human eye can actually perceive). This parameter can be found on some light bulb packaging and can be used to compare the luminous flux of one light source to another.

Macadam Ellipse

As stated in its classic definition, “The Macadam ellipses refer to the region on a chromaticity diagram which contains all colors which are indistinguishable to the average human eye, from the color at the center of the ellipse. The contour of the ellipse therefore represents the just noticeable differences of chromaticity.” In other words, the Macadam Ellipse defines the minimum color change that the human eye can perceive.

Comparing LED Light Sources

Calibrated Color Temperature (CCT)

CCT is one measurement used by the lighting industry to define the color quality of a warm or cool light source. The CCT describes the relative color appearance of a white light source, indicating whether it appears more red, yellow/gold, or blue, as compared to the range of what the human eye perceives as shades of white.

CCT is given in degrees Kelvin (K) and refers to the appearance of a theoretical black body heated to high temperatures. As the black body gets hotter, it turns red, orange, yellow, white, and finally blue. The CCT of a light source is the temperature at which the heated black body matches the color of the light source in question. Lamps with a CCT rating below 3200K usually are considered warm sources, whereas those with a CCT above 4000K usually are considered cool in appearance.

Currently, the CCT measurement is based in incandescence, therefore sources such as LEDs and arc lighting (everything from Compact Fluorescent to High Intensity Discharge) do not allow for a true direct comparison. For instance, an ordinary incandescent light bulb at 2900K will appear different to the eye than a fluorescing source that is rated at that same color temperature.

CRI

A more accurate measure of a light source is the Color Rendering Index (CRI). CRI is the measure of a light source's ability to faithfully reproduce colors when compared with a reference illumination. CRI as a uniform measurement is not without its faults. It provides a less accurate measurement at temperatures below 5000K. It is also measured differently in the Americas (by reflectivity) versus Europe (by spectral composition). However, it is still the one measurement that is currently accepted and used worldwide.

The reference point for CRI is typically standard daylight for higher color temperatures and an adjusted filter for lower color temperatures. Daylight is considered to have a CRI of 100; an incandescent halogen light bulb will have a CRI of 100 (for 3200K). Thus, a source with a lesser number will have compromises in faithful color reproduction.

CRI differences between various types of lighting can be shown in a spectrographic representation. The visual spectrum of a halogen light bulb is nearly a perfect black body radiator [Figure 3]. Compare this with the visual spectrum for a premium warm white fluorescent tube fixture [Figure 4] and then a less-than premium compact fluorescent [Figure 5].

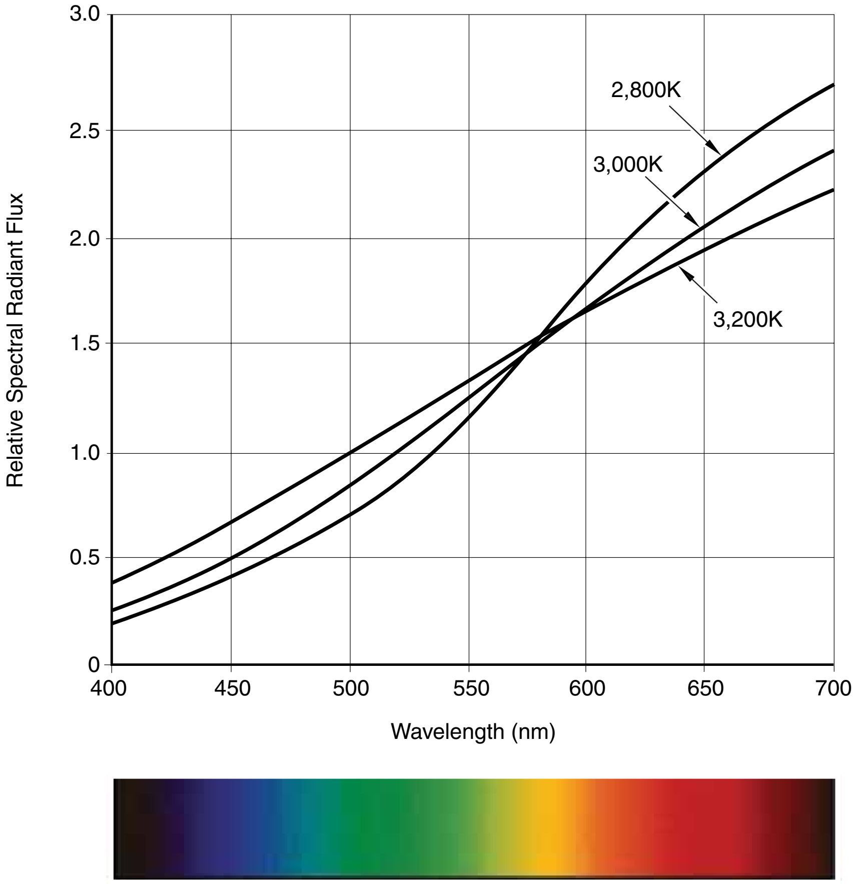


Figure 3: Incandescent spectral distribution: Note the strong infrared component and the lack of UV output.

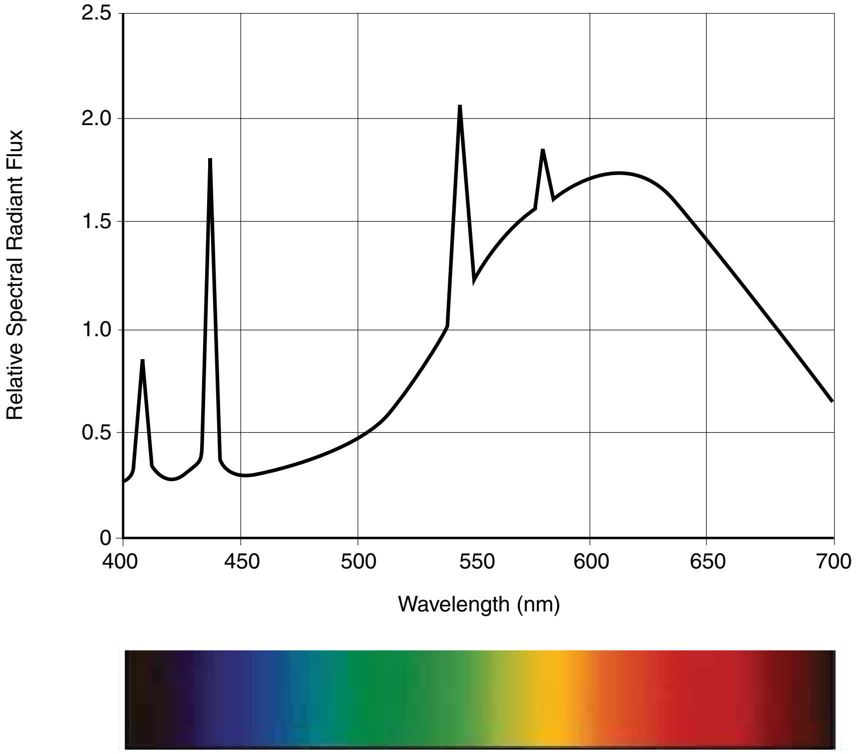


Figure 4: Premium warm white fluorescent spectral distribution: Note the spikes where the manufacturer has adjusted the output of the phosphors to provide a more pleasing light.

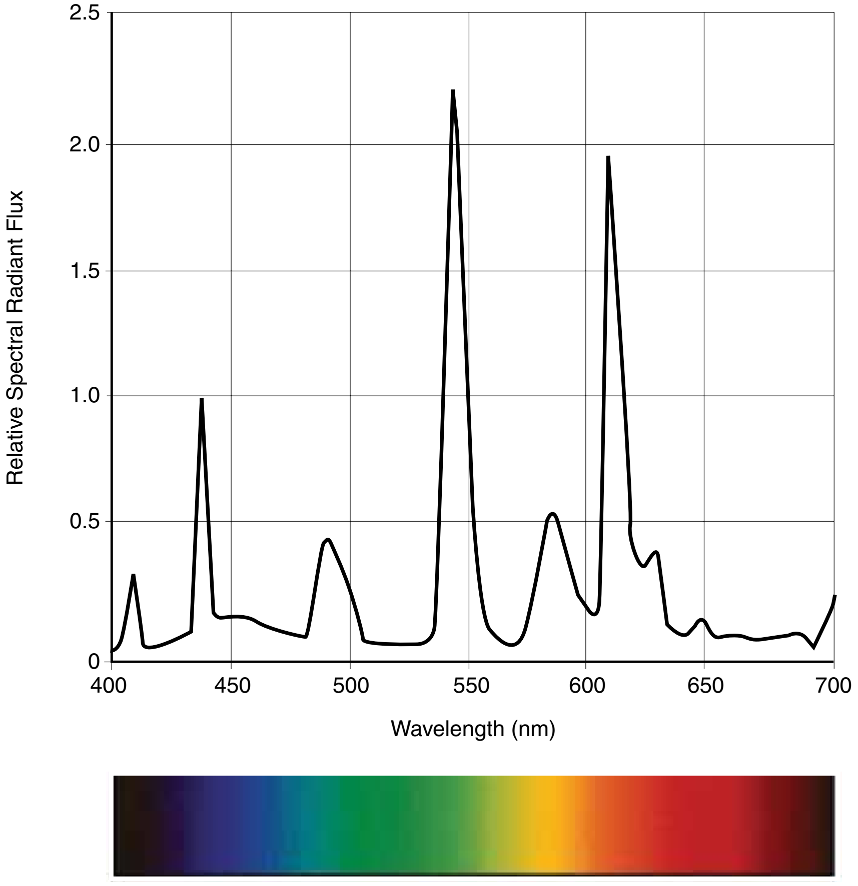


Figure 5: Less-than-premium compact fluorescent spectral output. The manufacturer has manipulated the yellow and orange output to make up for the strong green component in the output.

In the visual spectrum for an LED [Figure 6], note the lack of infrared energy (IR) and ultra-violet (UV) output from the device. This narrower light output spectrum has several positives. When used in outdoor fixtures, LED-based lighting lacks the UV output that draws insects. Indoors, the lack of IR output means that energy-to-light conversion inefficiencies aren't transferred to the objects being lit. Whatever is being lit will be bright without being heated by the luminaire.

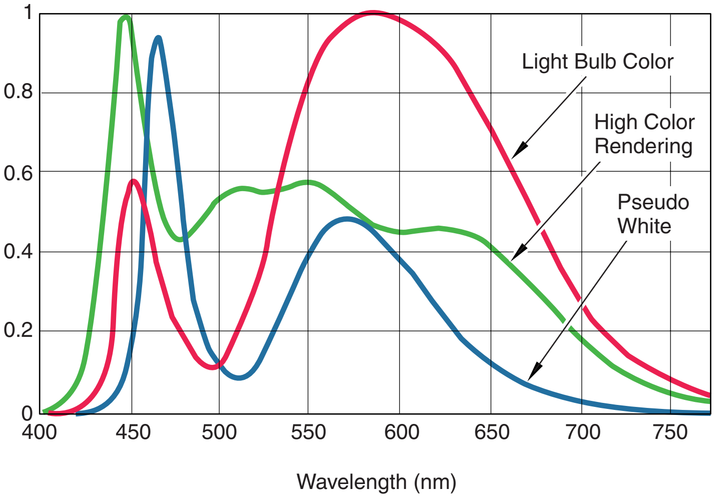


Figure 6: LED lighting module output. Note the lack of power output in the infrared or ultraviolet bands.

In the most ideal example, natural sunlight [Figure 7], note how the 6000K curve is the flattest – or most even – source of luminous radiation across all spectral bands. In the next chart [Figure 8], we see how the human eye is able to utilize this information in the beta, gamma, and rho areas – or what we call the R, G, and B (RGB) areas of daytime color vision.

In the day time, human eye is most sensitive to blue light. We perceive a great deal of our sensitivity to color shift information by what we get from the blue; we perceive detail through the red and green, with green being most prominent for luminance information. Television colorimetery is particularly helpful to explain this: Pure white, no matter what the display medium or phosphor, is made up of the ratio 76% Green, 22% Red, and 12% Blue. White is always this ratio for radiating devices.

Understanding these measurements is helpful, as overlaying Figures 7 and 8 with any of the preceding charts provides a qualitative idea of what "good quality" light might look like, where the goal is for the lighting fixture to reproduce as a "natural" light as possible. The output curves for these devices should closely match that of natural sunlight to have a light color and quality that is superlative. Flip back and forth between the sunlight and halogen lamp chart, and you can see that although the halogen has more red, it does a fair job of matching the curve of sunlight. When you look at the spiky quality of the fluorescent sources, you realize the lack of equivalent spectra that is visible to the human eye. High-quality LEDs fill these spectra in by design, thus creating a pleasing, higher-quality light.

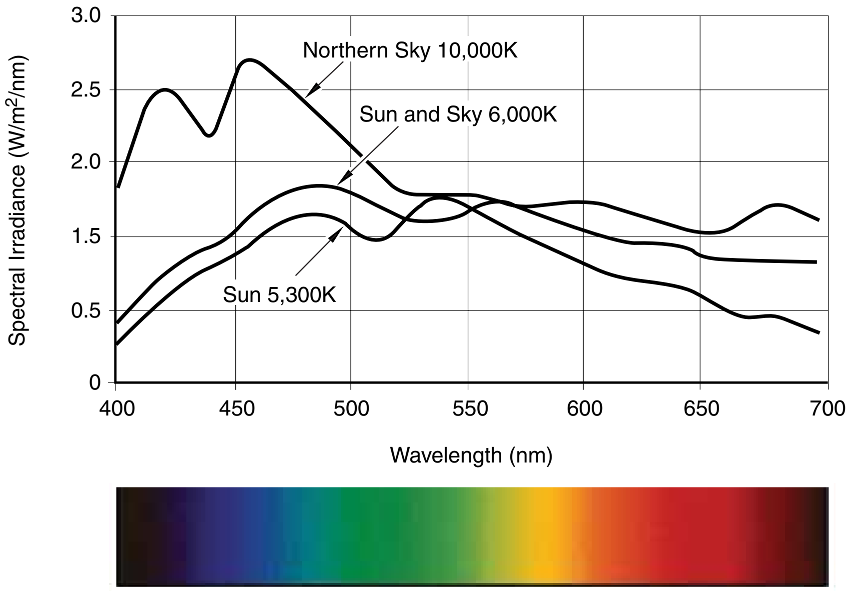


Figure 7: Sunlight spectral power: Note how much power is in the infrared and ultraviolet bands.

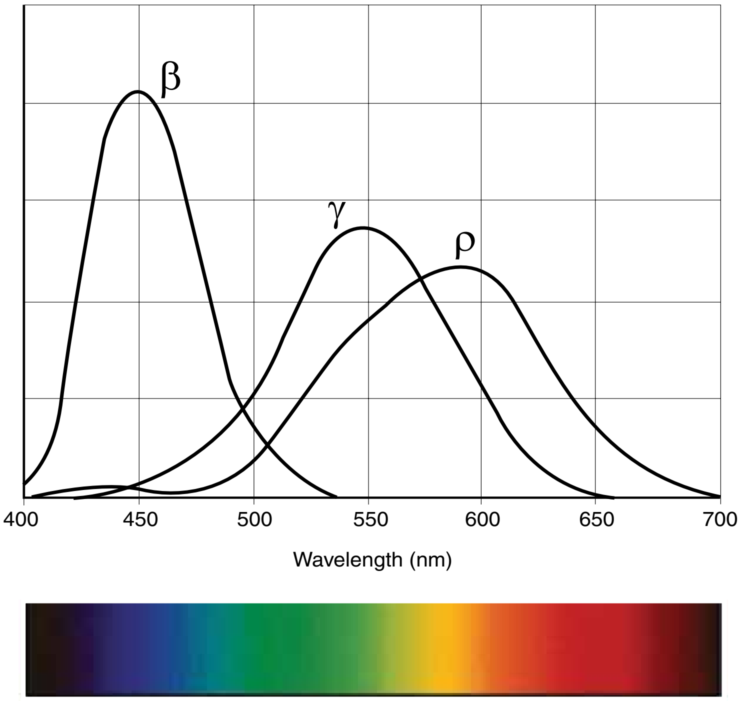


Figure 8: Human eye spectral sensitivity for daylight vision.

RGB and Ra Characteristics

Not all LED lighting is created equal. Some lighting modules, to achieve a better CRI and a better-looking light output, will incorporate devices with output specifically in the red, green, and blue spectrum. However, doing so impacts the price of the module, since more die are required per module. Other manufacturers use a phosphor material overlaid on a blue die to create the look of white light. This “pseudo-white” output can be adjusted to yield a high CRI, but attention must be paid to the actual color rendering of the part in critical applications.

Advanced new techniques are appearing, through select vendors, to infuse phosphor content necessary to create a light that has true-to-life rendering in the R9 area, which is required for correct and accurate production of deep reds. The resulting light has “warmth” and “depth” of color rendering that is unmatched by previous methods.

Design Considerations

In many ways, LEDs offer added flexibility for design. Small, individual LEDs allow for placement nearly anywhere and in almost any shape within a fixture, which offers far more design flexibility than a straight, rigid light rail and “off-the-shelf” bulbs.

For instance, one could use different color LEDs, say, a warmer color, in the upward radiating area of a luminaire, to ”warm up” a space with subtle, lower–temperature color, while the downward radiating area of that same luminaire could leverage a “cleaner” or “whiter” (i.e., higher color temperature, higher CRI) light for reading or task work.

While the learning curve is not prohibitive, it’s important to note that issues ranging from the way LEDs are powered and driven to the way they are dimmed require a different approach to design than systems based on more “traditional” types of lighting (incandescent, florescent, etc.). Following are a few of the most important concepts.

Powering LEDs

Unlike an incandescent lamp, the electronics used to power an LED lighting system are complex. LED-based lighting's first requirement is Direct Current (DC), since LEDs are direct current devices. The second requirement is a constant-current DC driver. Standard voltage-based design techniques for common light-emitting diodes cannot be applied when designing for LED lighting modules.

When LED lighting modules begin to conduct, they cease to act like standard light-emitting diodes: the forward voltage across the device begins to fall and current through the device increases correspondingly, depending on the device temperature. The higher the device temperature, the more likely it is to run away thermally.

This is a recipe for failure of the device if the current through the LED module is not limited properly. A simple resistor in line with it is not sufficient, as small changes in applied voltage will produce larger swings in current and the device's brightness. LEDs for lighting require careful current management,, because series currents that pass through the devices can be affected by temperature and applied voltage. This becomes important when driving large arrays of LED lighting devices. Although good design generally incorporates the use of a current-limiting resistor, this resistor is used more as a fuse in case of a mechanical short in the driven array of LEDs. Using current-based driving takes the pressure off the surrounding circuitry to provide precise voltages, and only requires that the minimum voltage along with the proper amount of drive current be available. The current driver also provides a measure of reliability in systems that will be exposed to extreme conditions. Light output will be consistent, no matter what the ambient temperature.

An LED driver is required in an LED system, similar to a fluorescent lighting system. Since the electric current passing through the LED must flow in one direction, Direct Current (DC) power must be used. A small fluctuation on the input forward voltage will cause wide variations in the current passing through the diode. The DC power source should be either a constant current or have a current limitation device.

Heat Management

Proper thermal management is extremely important when designing with LEDs, which are more sensitive to heat than some other types of devices. A recent advancement in heat management technology is the use of a wide ceramic substrate to achieve better heat dissipation, as well as high reliability. The ceramic substrate is an excellent way to get the heat out of the lighting LED, as it offers superior heat conduction over a greater area. Therefore, it is far more effective at dissipating the heat generated into the heatsink. Some other solutions rely upon heat conduction through the mounting lugs to handle the heat generated within the LED. The biggest challenge to any LED lighting design is the heatsink. However, doing this effectively means achieving high longevity of the part at its rated output.

LED Dimming

Attention must be paid to the drive electronics for both fluorescent- and LED-based lighting when designing a dimmable luminaire. Fluorescent bulbs require a dimmable ballast, and this ballast must quench the luminaire when the line voltage to it falls below a certain point and the arc can no longer be sustained. Otherwise, the life of the lamp will be severely shortened. Likewise, the fluorescent ballast must be of a special type, able to withstand the chopped AC, electrical noise, and voltage spikes created by inexpensive SCR dimmers. The complexity of a dimmable driver increases exponentially as the driver must accept what is now a highly distorted AC line waveshape, turn it into useable current, then power and dim its load accordingly with the input. This must be achieved without throwing a greater load upon the input line, since as voltage goes down, current must go up to maintain the same output.

If the luminaire will not be dimmed, then a relatively simple constant-current driver can be used. If the fixture will be dimmed, then the driver must be designed for dimming. Several solutions and technologies for dimming LED modules currently exist, and others are being introduced frequently.

Dimming a single LED device may be achieved by placing a resistor or variable resistor (potentiometer) in series with it; but this carries the risk of inconsistent light output, especially if the supply voltage to the series resistor is allowed to vary. Light output can also vary with ambient temperature using this method. A current regulator circuit may be a better solution. If you supply more current, the LED increases in intensity; by reducing the current, the LED will decrease in intensity.

Using an in-line resistor doesn't work as well for multiple LED configurations, such as series-parallel arrays. A better method in this case begins with the use of a current driver. A current driver circuit can keep the array from thermal runaway if driving it near its maximum-rated level, since the forward voltage tends to drop with increased heat in these types of devices. Dimming the array can now be accomplished through the use of Pulse Width Modulation (PWM). The PWM method can control the driver and therefore operate the array of LEDs with the recommended forward current. Dimming is achieved by turning the LEDs on and off at high frequency. PWM actually varies the duty cycle of the "on and off" portion of the current that feeds the LEDs. The frequency is fast enough that the human eye cannot see it; thus, dimming is efficiently achieved.

LEDs are quite robust and can handle the dimming very well, whereas dimming can be life-shortening to fluorescent lights. In low temperatures, the LEDs light instantly, while fluorescents require time and warmth to come to full brightness.

Lighting Applications

Quality of light in any design application is an ongoing compromise of many factors. Some applications demand a very high quality of light, where other applications are far less demanding.

For instance, lighting for retail environments demands high output for the amount of power consumed (efficacy), a specific amount of “hardness” or “softness” to the shadows being cast from the fixture (point source versus broad source), and very high accuracy of color for the object to be lit (color rendering). Color temperature (warm or cool) is an important factor, as well. Generally, the color of the display lighting must closely match lighting in other areas of the store (unless the display color is deliberately chosen to be different). As previously mentioned, LEDs also offer great flexibility to provide a mix of different qualities of light in the same fixture (e.g., warm uplighting and bright downlighting).

At the other end of the spectrum are applications such as area lighting and security lighting which generally demand high efficacy over other considerations. Some types of specialized lighting applications, including lighting for photography, television, and stage production, require extremely high power outputs and sacrifice other measures in favor of accurate and consistent color rendering.

A dramatic example of LED superiority over that of gas-discharge lighting is in that of industrial large-area lighting; for instance, landscape, street, and lot lighting. LEDs are more efficient than gas-discharge lighting, provide a more pleasant light, and last longer. Also, because their light does not contain any UV component, LEDs do not attract insects.

There is a wide range of general types of applications for LED lighting. Some include:

- General indoor and outdoor illumination
- Architectural illumination
- Commercial/residential directional lighting
- Stage lighting
- Reading lamps
- Spotlights
- Sign and symbol luminaries

Many applications also benefit from “smart” features such as light sensors. Light sensors are being integrated into products more and more frequently as a power-saving, environmentally-friendly feature.

LED Advantages

LED bulbs offer a number of significant advantages over other lighting types. One is longer operating life; up to 50,000 hours to half brightness with LEDs. This is 60% longer life than an average long-life sodium-vapor commercial luminaire.

As previously mentioned, LEDs also offer increased durability because they are solid state devices, and LEDs also offer more design flexibility given their small footprint and freedom of placement. For instance, certain types of arch lighting and other creative lighting solutions that mount lights on curved surfaces are newly enabled by LEDs.

The growing popularity of LEDs is also linked to their benefit to the environment. They require little energy to operate, and lack hazardous materials such as Mercury (Hg). It is likely that the adoption of LEDs into lighting designs will continue to increase due to their earth friendliness, driven by both customer awareness and increasing legislation related to energy conservation.

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