

Color Quality of White LEDs

Color quality has been one of the key challenges facing white light-emitting diodes (LEDs) as a general light source. This fact sheet reviews the basics regarding light and color and summarizes the most important color issues related to white light LEDs, including recent advances.

Unlike incandescent and fluorescent lamps, LEDs are not inherently white light sources. Instead, LEDs emit light in a very narrow range of wavelengths in the visible spectrum, resulting in nearly monochromatic light. This is why LEDs are so efficient for colored light applications such as traffic lights and exit signs. However, to be used as a general light source, white light is needed. The potential of LED technology to produce high-quality white light with unprecedented energy efficiency is the impetus for the intense level of research and development currently being supported by the U.S. Department of Energy.

White Light from LEDs

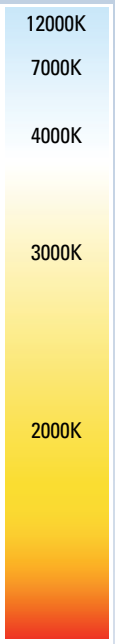
White light can be achieved with LEDs in two main ways: 1) phosphor conversion, in which a blue or near-ultraviolet (UV) chip is coated with phosphor(s) to emit white light; and 2) RGB systems, in which light from multiple monochromatic LEDs (red, green, and blue) is mixed, resulting in white light.

The phosphor conversion approach is most commonly based on a blue LED. When combined with a yellow phosphor (usually cerium-doped yttrium aluminum garnet or YAG:Ce), the light will appear white to the human eye. Research continues to improve the efficiency and color quality of phosphor conversion.

The RGB approach produces white light by mixing the three primary colors - red, green, and blue. The color quality of the resulting light can be enhanced by the addition of amber to “fill in” the yellow region of the spectrum. Status, benefits, and trade-offs of each approach are explored on page 2.

Correlated Color Temperature (CCT)

CCT describes the relative color appearance of a white light source, indicating whether it appears more yellow/gold or more blue, in terms of the range of available shades of white. CCT is given in Kelvin (SI unit of absolute temperature) 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 (in K) at which the heated black body matches the color of the light source in question.

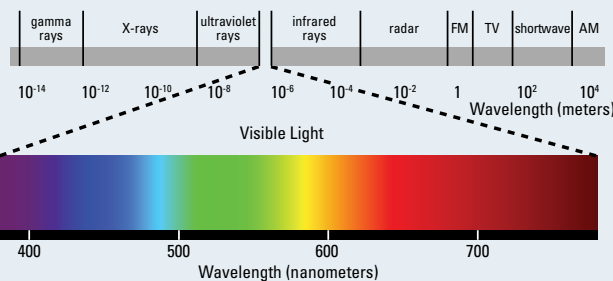


Color Rendering Index (CRI)

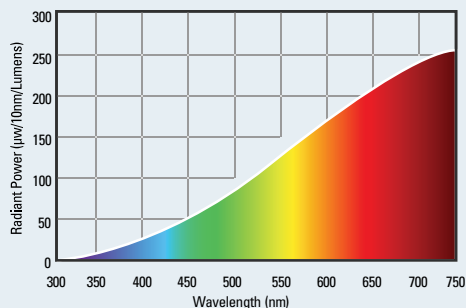
CRI indicates how well a light source renders colors, on a scale of 0 to 100, compared to a reference light source of similar color temperature. The test procedure established by the International Commission on Illumination (CIE) involves measuring the extent to which a series of eight standardized color samples differ in appearance when illuminated under a given light source, relative to the reference source. The average “shift” in those eight color samples is reported as Ra or CRI. In addition to the eight color samples used by convention, some lighting manufacturers report an “R9” score, which indicates how well the light source renders a saturated deep red color.

What is White Light?

We are accustomed to lamps that emit white light. But what does that really mean? What appears to our eyes as “white” is actually a mix of different wavelengths in the visible portion of the electromagnetic spectrum. Electromagnetic radiation in wavelengths from about 380 to 770 nanometers is visible to the human eye.



Incandescent, fluorescent, and high-intensity discharge (HID) lamps radiate across the visible spectrum, but with varying intensity in the different wavelengths. The spectral power distribution (SPD) for a given light source shows the relative radiant power emitted by the light source at each wavelength. Incandescent sources have a continuous SPD, but relative power is low in the blue and green regions. The typically “warm” color appearance of incandescent lamps is due to the relatively high emissions in the orange and red regions of the spectrum.



Example of a Typical Incandescent Spectral Power Distribution



Comparison of White Light LED Technologies

Each approach to producing white light with LEDs (described above) has certain advantages and disadvantages. The key trade-offs are among color quality, light output, luminous efficacy, and cost. The technology is changing rapidly due to intensive private and publicly funded research and development efforts in the U.S., Europe, and Asia. The primary pros and cons of each approach at the current level of technology development are outlined below.

Technology	Advantages	Disadvantages
Phosphor conversion	<ul style="list-style-type: none"> • Most mature technology • High-volume manufacturing processes • Relatively high luminous flux • Relatively high efficacy • Comparatively lower cost 	<ul style="list-style-type: none"> • High CCT (cool/blue appearance) • Warmer CCT may be less available or more expensive • May have color variability in beam
RGB	<ul style="list-style-type: none"> • Color flexibility, both in multicolor displays and different shades of white 	<ul style="list-style-type: none"> • Individual colored LEDs respond differently to drive current, operating temperature, dimming, and operating time • Controls needed for color consistency add expense • Often have low CRI score, in spite of good color rendering

Most currently available white LED products are based on the blue LED + phosphor approach. A recent product (see photo below) is based on violet LEDs with proprietary phosphors emphasizing color quality and consistency over time. Phosphor-converted chips are produced in large volumes and in various packages (light engines, arrays, etc.) that are integrated into lighting fixtures. RGB systems are more often custom designed for use in architectural settings.

Typical Luminous Efficacy and Color Characteristics of Current White LEDs

How do currently available white LEDs compare to traditional light sources in terms of color characteristics and luminous efficacy? Standard incandescent A-lamps provide about 15 lumens per watt (lm/W), with CCT of around 2700 K and CRI close to 100. ENERGY STAR-qualified compact fluorescent lamps (CFLs) produce about 50 lm/W at 2700-3000 K with a CRI of at least 80. Typical efficacies of currently available LED devices from the leading manufacturers are shown below. Improvements are announced by the industry regularly. Please note the efficacies listed below do not include driver or thermal losses.



Photo credit: Vio™ by GE Lumination

CCT	CRI	70-79	80-89	90+
2600-3500 K		23-43 lm/W		25 lm/W
3500-5000 K		36-73 lm/W	36-54 lm/W	
> 5000 K		54-87 lm/W	38 lm/W	

Sources: Manufacturer datasheets including Cree XLamp XR-E, Philips Lumileds Rebel, Philips Lumileds K2.

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

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