High Performance Multi-Color LEDs in COB Technology

LED Solutions® by PerkinElmer

WHITE PAPER

Introduction

Since 1962, when the first red Gallium-Arsenide-Phosphide (GaAsP) light emitting diode (LED) was produced, a great deal of time, money and effort has been spent on developing more efficient LEDs to compete with other light sources. By 2000, “power chips” or “high-current chips” were developed for serial production. These chips enabled LEDs to effectively penetrate a variety of markets for different white and color lighting applications.

High-performance LEDs, designed and manufactured as multi-chip high-power LEDs in chip-on-board (CoB) technology, are a brilliant example of multifunctional devices for white and color LED applications. Obviously, specific requirements must be met for developing such high-power LEDs. Most of the electrical input power is converted into heat, which makes thermal management a key consideration. Also, intelligent optical layout of the LED is crucial since this enables increased efficiency as well as optimal color-mixing quality.

Whereas conventional illuminants, such as light bulbs, halogen or fluorescent light sources, show continuous spectra and generate mostly unwanted infrared (IR) radiation, color LEDs have more discrete spectra and need a heat conductive process to eliminate generated heat. A more detailed explanation is provided later in this paper.

Of course, LEDs are the more favored solution regarding effectiveness for colored applications because they do not need the additional filtering that is characteristic of conventional light sources. Color LEDs can even be useful in applications that require white light or with a high color-rendering index.

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1 Design and Construction

In the design and construction of a high-performance, multi-color LED in COB technology, an LED design with four high-power chips (sized ~ 1x1 mm^2) is an excellent solution due to its optical performance and multi-functionality. An adequate LED board can, for instance, be based on an insulated metal substrate (IMS) made from copper and a highly-sophisticated isolation material with a low thermal resistance between the copper and chip pads. Such a package provides excellent heat dissipation and thermal management from the chip to the board's backside. The thermal resistance ($R_{th,JB}$) of an entire package is quite low (~4.5 K/W), depending on the chip configuration. To dissipate the heat, adequate cooling must be considered. To avoid overheating damage to LED chips equipped with at least one high-power LED chip, the LED must not run without appropriate cooling – even at lower currents.

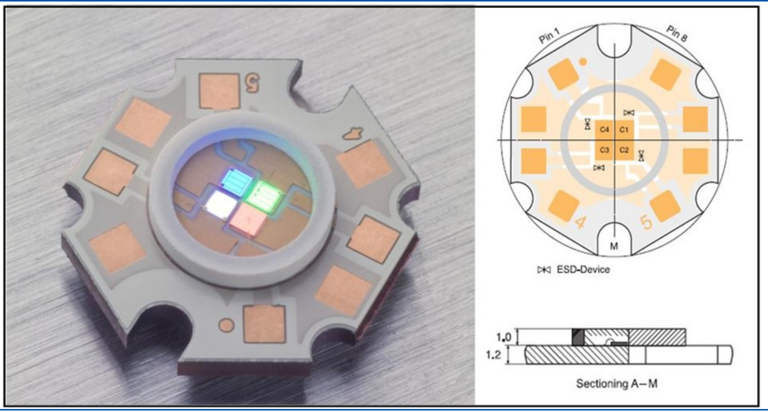

Figure 1: Example of high-performance multi-color LED in CoB
(PerkinElmer's ACULED® VHL™ RGBW)

Figure 1 shows the typical layout of a high-performance, multi-color LED. The chips are placed in the middle of the board, protected by a PPA-based ring and silicone resin encapsulation. The latter is transparent and suitable for a wide radiation range from ultraviolet (UV) to IR. These characteristics achieve superior light radiation resistance, degradation mitigation, and the ability to maintain LED color purity over the LED's lifetime.

The distance between the LED chips should be minimal and, in special cases, may be down to 0.1 mm for achieving the best color mixing. To allow all four chips (and colors) to be operated and adjusted separately for maximum flexibility of the electrical driving layout, each chip should have a separate anode and cathode. If electro-static discharge (ESD)-sensitive LED chips are implemented in a package, ESD protection diodes can enhance reliability and should, therefore, be optionally available in any high-performance LED package.

A design with four closely-placed chips (see Figure 1) will have a small, but bright, light-emitting area that achieves excellent color mixing with multi-color configurations. A high-precision chip placement with less than 20 µm placement tolerance to a reference mark makes it a superior and reliable light tool, especially when used with optics. For easy and cost-effective process flow, the high-performance, multi-color LED should be supplied in a package that allows automatic pick-and-place processing, such as a standard blister tape.

Modern high-power LED chips that are mandatory for high-performance LEDs have efficiencies of 10% to 50% of radiation output at common operation conditions. Thus, 50% to 90% of the electrical energy is transformed into heat. In contrast to incandescent lights, almost no heat is radiated into the LED's environment in terms of IR radiation. However, during operation, heat is still generated and has to be mitigated by thermal conduction to avoid undesirable effects, or even destruction, of the LED chip.

Besides helping to avoid chip damage from overheating, good thermal management helps handle all parameters impacted by temperature, including:

- lifetime [t_{Life}] / degradation
- forward voltage [V_F]
- flux [Φ_e and Φ_V]
- wavelength [λ] resp. color [$x_{2°}$ / $y_{2°}$] and color temperature (T_{CT}).

It is essentially to work under stable conditions that reduce degradation, forward voltage drift, flux instabilities and wavelength shift, particularly during color mixing of a multi-color LED. To achieve optimal performance, it is, therefore, helpful to minimize thermal crosstalk between the LED chips, much like in an excellent LED-array. With low thermal crosstalk, the heating up of one LED chip has minimal effect on neighboring chips, resulting in excellent constancy in the parameters described above.

The LED array must be attached to a heat sink or heat-conducting board. Besides mechanical stability, cooling is the key consideration of the assembly process. The heat must be drawn away from the LED board by conduction. A good physical contact between the substrate and the heat sink must be established for adequate heat transport. Because of this need for good contact, screwing is the best choice for mounting whenever possible. The mounting technique should also consider the stability required by the application. Mobile execution with higher vibration, for example, requires more stability than stationary applications.

1.1 Influence on Lifetime

Overheating an LED chip, such as exceeding its junction temperature (T_J) over the allowable maximum, will damage the chips within a short time. But long-term temperature effects also influence lifetime. During operation, a lower temperature corresponds with a longer chip lifetime and, in turn, a longer lifetime for the entire color LED product. Some degeneration processes require a minimum temperature, thus, a low T_J will dramatically increase the product's lifetime. Since these processes are very complex and not fully understood today, it's virtually impossible to get reliable curves of t_{Life} versus T_J for a longer period of time.

1.2 Influence on Forward Voltage

The forward voltage (V_F) typically decreases in the range of several mV per Kelvin with increased temperature. The temperature-induced forward voltage variation can be assumed as linear over the typical temperature changes during operation. The typical curves for red, green and blue chips (see Figure 2) show that this issue should be considered for multi-color LED designs with appropriate electrical circuitry.

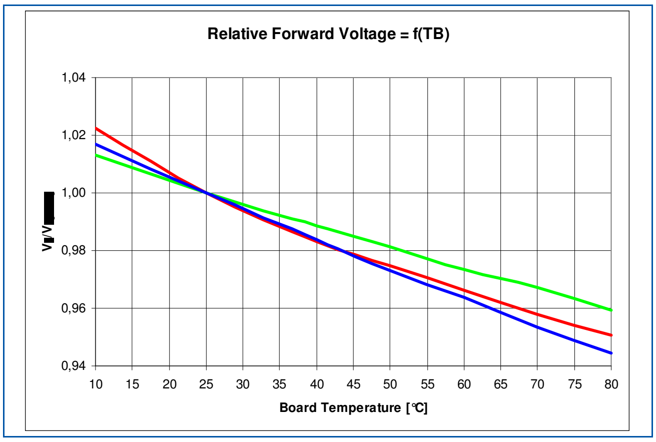

Figure 2: Relative forward voltage versus LED board temperature T_B for red, green and blue chips (ACULED)

1.3 Influence on Flux and Intensity

The flux (Φ_e) and (Φ_V), along with their deducted values, such as luminance, radiance, luminous intensity or radiant intensity, decreases with increasing temperature. Generally speaking, the intensity drop of blue and green Indium-Gallium-Nitride (InGaN)-based chips is usually small, whereas the drop with yellow, amber and red Aluminum-Indium-Gallium-Phosphide (AlInGaP)-based chips is larger. Figure 3 shows typical curves representing the relative luminous drift for the chips of an RGYB four-chip LED.

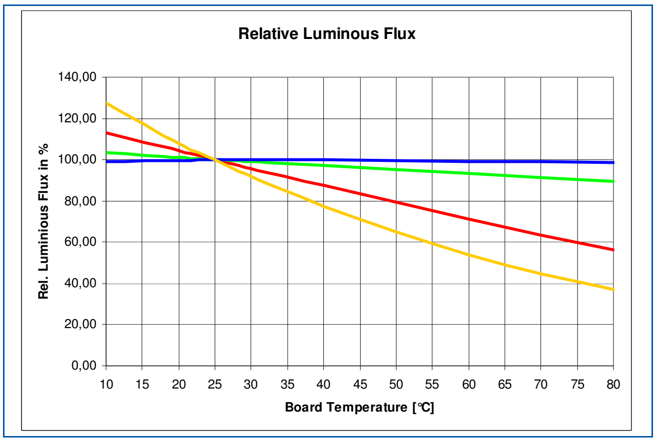

Figure 3: Change of relative luminous flux vs. board temperature T_B for the chips of an RGYB-LED

If a certain flux is necessary in an application, it's important to level out the temperature-based intensity drop. A good thermal management also helps the drift to stay as low as possible. The balancing of the drift over temperature is important, particularly when using chips of different colors on an LED, such as RGGB or RGYB. It helps maintain the same intensity ratio and, therefore, the same color appearance. With the RGYB, for example, the color mix drifts to a blue-greenish light with increasing temperature, since yellow and red fade out much more than blue and green (see Figure 3). If the LED-package shows no thermal crosstalk between the chips, as described above, each chip can be leveled out individually without regard for its temperature or heating effects on neighboring chips.

Besides changing the mixed color ratio due to the different intensity changes, each chip also changes color as a result of wavelength drift caused by temperature (see Figure 4).

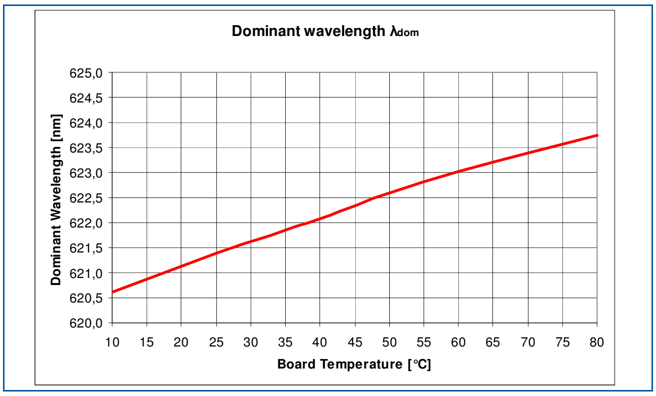

Figure 4: Change of peak wavelength vs. substrate temperature T_B for the chips of an RGYB-LED

Consideration for the above-mentioned aspects will enable the design and manufacture of tunable high–performance, multi-color LEDs that can penetrate various applications. These applications include architectural and landscape lighting; entertainment and mood lighting; medical and operational lighting; and displays or signs. With the high requirements of entertainment or operational medical lighting, for example, a brilliant color reproduction is required. The comparison below of different light sources with high-performance, multi-color LEDs underscores the multi-functionality of the latter LED-types.

2 Color Rendering of Different Light Sources

As a simplified qualitative approach, different well-known light sources can be observed for their ability to reproduce the different colors of a color stripe master lit by the source.

Figure 5 shows the master, divided into different groups of red, green and blue. As first light source, a well-known commercial incandescent light with approx. 2800K correlated color temperature is chosen. Taking the spectrum (see Figure 6) of such a light source, it is easy to recognize the nearly linear behavior. It has a predominant part of red and, therefore, leads to that nice warm white that is very comfortable for the human eye. As expected, red colors are highlighted by the light source (see Figure 6). For blue colors, the light source generates weak blue tones and even shifts the green colors to warmer yellowish. Halogen light sources generally show this behavior with slightly a different color temperature of approximately 3200K. If unfiltered, neither would be useful for medical operational lamps since the requirements dictate a white with higher color temperature.

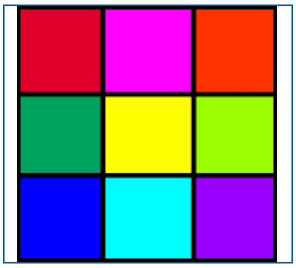

Figure 5: Master of different color groups

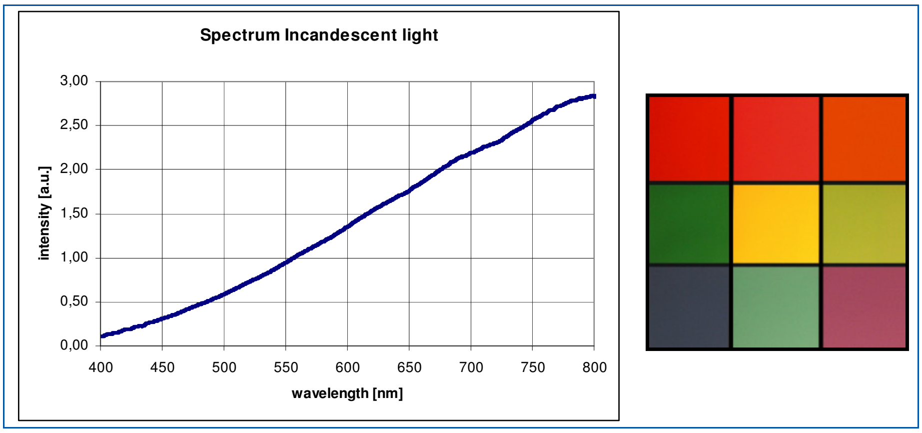

Figure 6: a) spectrum of incandescent light
b) color rendering of a light bulb

Choosing a standard fluorescent lamp as a light source, the continuous, but rippled, spectrum can be observed with various spikes (see Figure 7). Along with the very sharp spikes, there is also a reasonably flat spectrum across the entire visible wavelength range. The corresponding color rendering, shown in Figure 7, shows acceptable color diversity. However, the quality of the color rendering strongly depends on the spectrum of the specific fluorescent lamp and can be up to 90%.

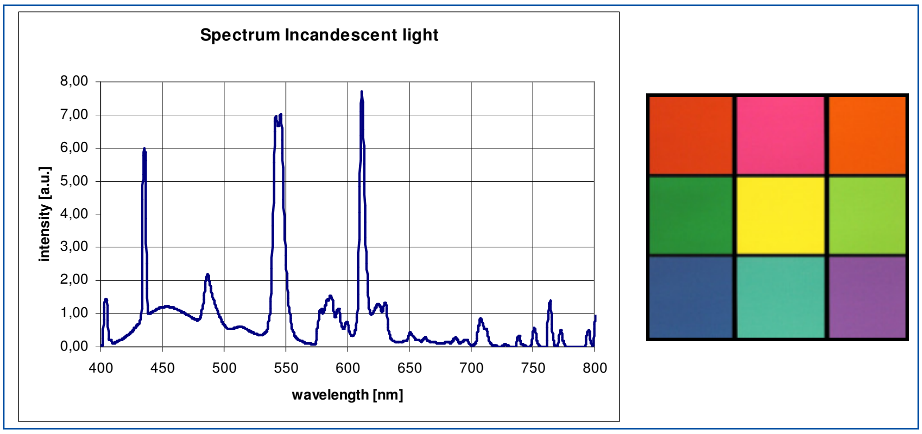

Figure 7: a) color rendering of a fluorescent tube
b) spectrum of a fluorescent tube

In contrast to observed light sources with continuous spectra, LEDs with their discrete spectra will be analyzed in more detail. The most traditional method for achieving white light with acceptable color rendering is to take blue LEDs with a yellow converter. The converter can either be directly attached on the LED chip or placed above as volume coating or layer for other attached components. To achieve the best efficacy, converter materials for cold white LEDs are typically used instead of warm white converter materials that are less efficient. The typical spectrum of a cold white LED is shown in Figure 8, lacking cyan and red colors in the spectrum. The corresponding color rendering of the master underscores the weak performance for the illumination of red objects.

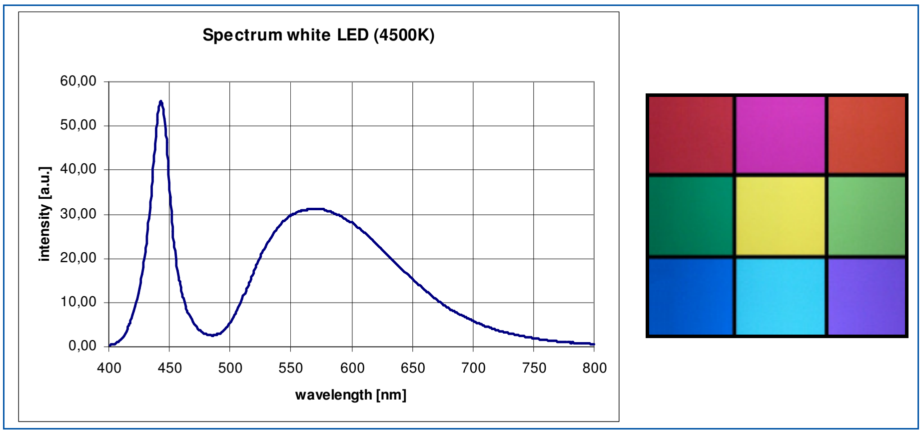

Figure 8: a) spectrum of a cold white LED
b) color rendering of a cold white LED

An alternative method for achieving white with LEDs is to use an RGB LED, such as PerkinElmer´s four-chip high-power LED ACULED. The LED's spectrum is shown in Figure 9. For this particular LED, four very tightly placed chips, including two green, are used. The configuration and performance of all chips within this RGB-LED lead to a white light generation when operating each chip close to the maximum rated current. The color rendering performance (see Figure 9) is limited by the "discrete" spectra of the single-color LEDs and shows limited performance on yellow. However, the red and blue LEDs show excellent performance and high brilliance.

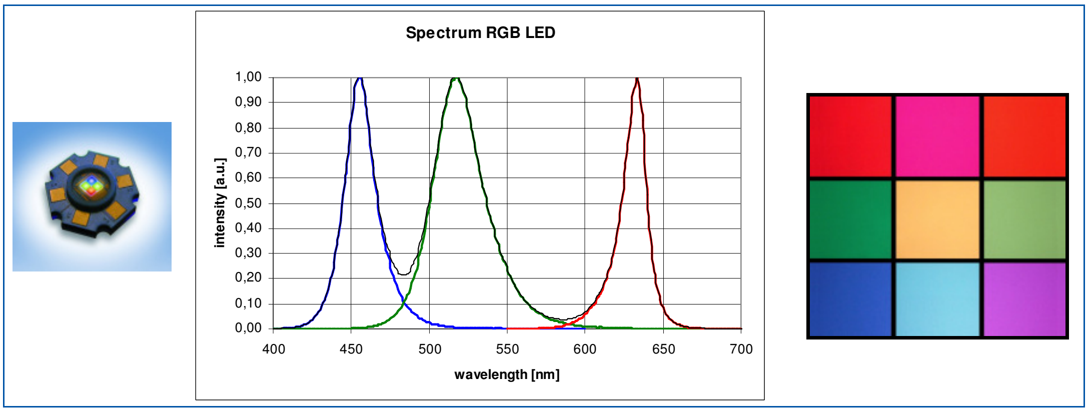

Figure 9: a) RGGB LED ACULED
b) spectrum
b) color rendering

The RGGB LED enables individual mixture of colors, as seen in the CIE 1931 diagram shown in Figure 10, including virtually every white color temperature, such as ~6000 K or 3100 K (see Figure 10).

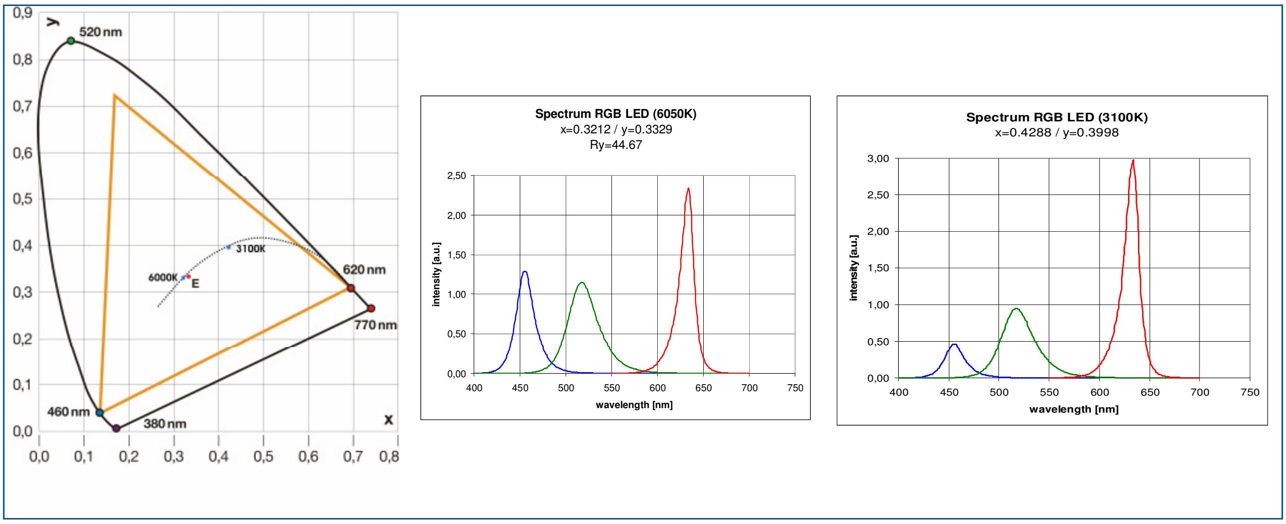

Figure 10: a) achievable chromaticity coordinates within CIE 1931 diagram for RGGB LED
b) spectra for achieving 6000 K white
c) spectra for achieving 3200 K white

Adding a yellow LED chip that closes one spectral gap will enhance the results (see Figure 11). Nevertheless, the yellow chips have very low efficiencies when compared to the red, green and blue chips.

The above results ultimately conclude that a combination of white converted LEDs with red, green and blue LEDs will achieve a highly-efficient multi-color LED (see Figure 1), including excellent color rendering and color tunability. Figure 12 shows the spectrum and results for the illuminated color stripe with an RGB White (RGBW) - LED.

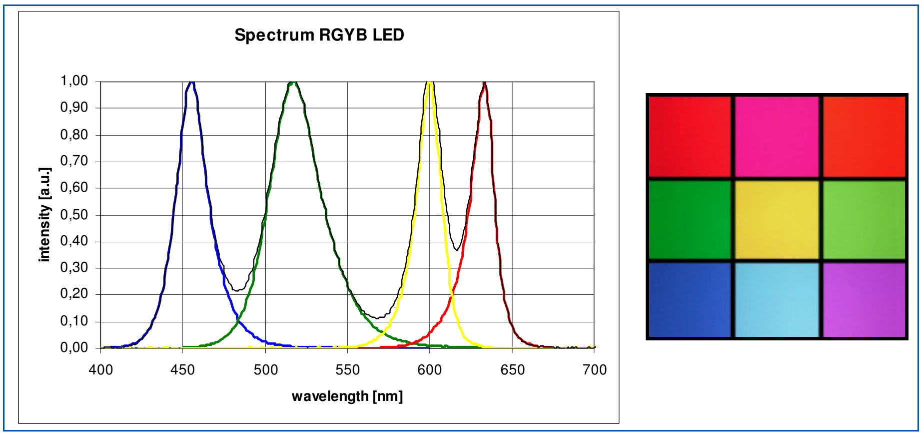

Figure 11: a) color rendering of ACULED VHL RGYB
b) spectrum of ACULED VHL RGYB

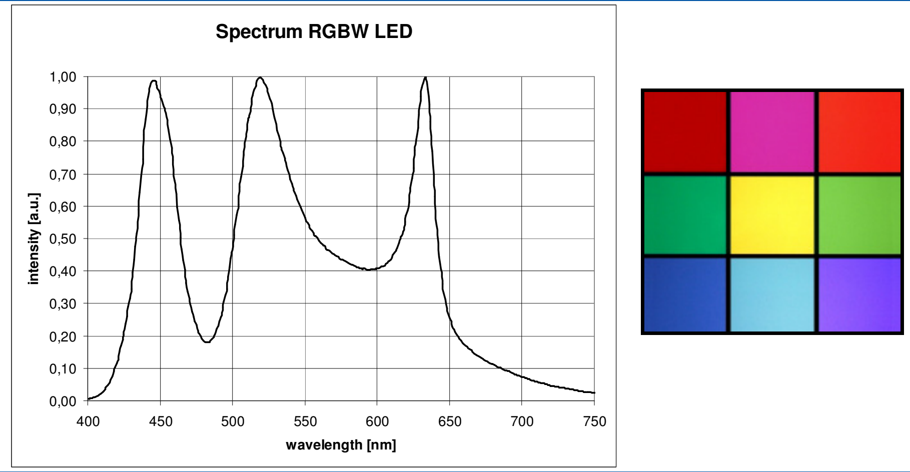

Figure 12: a) color rendering of ACULED VHL RGBW
b) spectrum of ACULED VHL RGBW

The actual LED chip generation and state-of-the-art packaging technologies make such RGBW LEDs ideal light sources for a wide variety of in both general and specialty lighting applications.

The achievable high color rendering indices of RGBW LEDs allow their use, for example, in operational lamps and add the ability to change color temperatures, if necessary. Taking an all-in-one unit with the tightest possible chip spacing (see Figure 1) will also reduce cast shadows, with or without additional optical beam shaping.

Another possible application is in entertainment lighting, particularly stage or film studio lighting. These products require excellent color rendering and the ability to change colors within a large color space – easily achievable with RGBW-LEDs.

The two examples above show the potential of high-performance, multi-color LEDs. These LEDs are poised to rapidly penetrate applications with comparable requirements due to the ever-increasing efficiency of chips and packages, as well as steadily decreasing LED costs.

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