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Impact of Dimming White LEDs: Chromaticity Shifts Due to Different Dimming Methods

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ABSTRACT

The goal of this study was to characterize the chromaticity shift that mixed-color and phosphor-converted white LED systems undergo when dimmed. As light-emitting diodes continue to rapidly evolve as a viable light source for lighting applications, their color shift while being dimmed should meet the current requirements of traditional lighting sources. Currently, LED system manufacturers commonly recommend pulse-width-modulation or PWM dimming schemes for operation of LED systems. PWM has the ability to achieve lower intensity levels and more linear control of light intensity compared to continuous current dimming methods. However, little data has been published on the effect dimming has on chromaticity shift of white LED lighting systems.

The primary objective of this study was to quantify chromaticity shifts in mixed-color and phosphor-converted white LED systems due to continuous current dimming and pulse-width-modulation dimming schemes. In this study, the light output of the LED system was reduced from 100% to 3% by means of continuous current reduction or PWM methods using a PC white LED system and a mixed-color RGB LED system. Experimental results from this study showed that the PC white LED system exhibited very little chromaticity shift (less than a 4-step MacAdam ellipse) when the light level was changed from 100% to 3% using both dimming schemes. Compared to PC white LEDs, the mixed-color RGB LED system tested in this study showed very large chromaticity shifts in a similar dimming range using both dimming schemes. If a mixed-color RGB system is required, then some active feedback system control must be incorporated to obtain non-perceivable chromaticity shift. In this regard the chromaticity shift caused by the PWM method is easier to correct than the chromaticity shift caused by the continuous current dimming method.

Keywords: LED, white light LED, mixed-color white LEDs, architectural lighting, PWM, color shift

1. INTRODUCTION

In architectural lighting applications, dimming of light sources is an essential feature to meet the functional and aesthetic requirements of a space. In conference rooms, for example, dimming of the room lights is common, especially during slide or media presentations. Reducing light levels in a restaurant can provide an intimate environment for fine dining while also adding to the aesthetics of the space. In addition, dimming is commonly used for energy conservation purposes. Although it is common in workplaces to see lighting kept at constant levels throughout the day, office tasks may not require the same level of illumination at all times. As an example, 300 lx (30 fc) may be needed if someone is performing a reading or writing task, whereas the same person may need only 30 lx (3 fc) for computer tasks [1]. Having the capabilities to dim lights can improve the work environment within the space as well as conserve energy.

Traditional lighting sources typically used for these applications are incandescent, fluorescent, and metal halide lamps, all of which behave differently when dimmed. A rapidly evolving light source technology that is showing promise for specialized and general illumination applications is white light light-emitting diodes (LEDs). Similar to other light sources presently used in general lighting, white LEDs have to cater to the dimming needs of general illumination and conform to color-shift requirements. In general, noticeable color shift during dimming is not desirable. Since white LED technology is quite new, less information is available regarding its behavior while being dimmed. Therefore, the purpose of this research is to better understand the behavior of white LEDs during dimming.

1.1 Dimming methods

There are two general methods to generate white light with LEDs. The first is by the use of phosphors together with a short-wavelength LED, resulting in a broadband radiation spectrum, referred to as a phosphor-converted white LED, or PC white LED [2-5]. The second method is to utilize mixed light from two (dichromatic), three (trichromatic), or more (tetrachromatic, for example) LEDs emitting different narrow bands of radiation. To achieve reasonable color-rendering properties, at least three colors (R,G,B) must be combined. The advantage to using an RGB source is that any shade of white can be created by controlling the ratios of each red, green, and blue component. Maintaining color balance is critical, considering that the radiated emission spectra from each individual device respond differently to changes in temperature and current, and experience different rates of degradation over time.

Semiconductor LEDs have a non-linear relationship between current and voltage, unlike that of a resistor in which the current and voltage change linearly. If the voltage supplied to an LED is varied even by a small amount, the current or effective light output of the LED changes significantly, resulting in difficulty achieving precise control of light output. Conversely, small changes in current result in small light output changes. Therefore, a current-controlled method is a preferred way to drive LEDs. Dimming white light LED systems can be accomplished by two techniques: continuous current reduction and pulse-width-modulation (PWM). Continuous current reduction is a method in which the decrease in current causes the decrease in light output, whereas changes in the duty cycle allow for control of the light output in PWM. Each of these techniques could impact the chromaticity point of white LED systems.

The current dimming scheme exploits the linear section of the I-V relationship. Throughout this linear range, as the current is reduced, the light output will reduce proportionally. With this method, dimming in the range from 100% to 10% of maximum is achievable (dimming below 10% is difficult) and offers a simple and cost-effective means of dimming LEDs. Because LEDs are semiconductor devices, they can be turned on and off rapidly, making dimming LEDs with PWM methods possible. This common dimming technique uses simple on-off switching to produce the effect of variable voltage by controlling the average current to the LED. This method provides the ability to increase the dimming range by achieving lower current levels and linear control of light intensity down to zero percent. Usually a high modulation frequency is used to prevent the perception of individual light pulses, causing a flickering effect.

The duty cycle, as shown in Figure 1, is expressed as the ratio between pulse duration and signal period, or the amount of time the pulse is high (the pulse width) divided by the total period of the pulse:

$$D = \frac{\tau}{T} \tag{Equation 1}$$

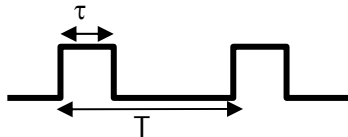


Figure 1: Graphical representation of duty cycle

where D , τ , and T are the duty cycle, pulse width, and period, respectively. In a PWM scheme, the forward current I_f is kept at a constant value and only the duty cycle is changed. The average current of a PWM signal can be related to the peak current by Equation 2.

$$I_{AVG} = (I_{PEAK})(D) \tag{Equation 2}$$

In general, pulse-width-modulation has greater appeal over continuous current reduction when dimming a light source because of its increased dimming range and greater efficiency.

1.2. Color appearance and chromaticity shift

Chromaticity values are commonly used for characterizing the color appearance of a light source. A metric commonly used for quantifying perceivable color difference is the MacAdam ellipse, which is a contour in the chromaticity diagram [6]. If the chromaticity coordinates of two white light sources fall beyond this region, then almost all color-normal subjects will perceive a color difference between these two sources [6]. The American National Standards Institute (ANSI) specified a 4-step MacAdam ellipse as the acceptable chromaticity tolerance area for certain types of fluorescent lamps [7].

Past literature was thoroughly searched to understand what information exists regarding the chromaticity shift of white LEDs when dimmed. Chromaticity shift results from changes in spectral power distribution (SPD), including, amplitude, peak wavelength, and the shape of the spectrum. In the case of RGB mixed-color white LED systems, even small amplitude and peak wavelength position changes (less than 1 percent change in amplitude and 1 nm shift in peak wavelength) of certain colored LEDs can cause perceivable color changes [4].

Many past studies have cited heat at the junction of the LED to cause the spectrum to change amplitude, peak wavelength position, and shape (Kish and Fletcher [8], Nakamura [9], Tamura [10]). Hong et al. (2003) found that for AlInGaP red LEDs, the peak wavelength position changes linearly with junction temperature, regardless of how heat is added to the junction. Red, green, and blue LEDs have different sensitivities to heat: the light output of red LEDs changes the most with heat, followed by green, and then blue [11].

Studies have shown that current density can also affect the spectrum. With increasing forward current, light output increases. However, the junction also gets hotter with increasing current, causing the light output to decrease. Muller-Mach et al. (2002) showed that the spectrum of InGaN-based blue LEDs shifts toward shorter wavelengths with increasing drive current; however, it also shifts toward longer wavelengths when the junction heat is increased [5].

2. EXPERIMENT

None of the past studies have systematically quantified the chromaticity shifts of white LEDs (mixed-color and phosphor-converted) when using different dimming schemes (continuous current dimming or PWM dimming). Therefore, the objective of this study was to quantify chromaticity shifts in mixed-color and phosphor-converted white LED systems due to continuous current dimming and pulse-width-modulation dimming schemes. Four types of high-power LEDs were used: red, green, blue, and white, all from the same manufacturer.

Figures 2(a) and 2(b) illustrate the LED system used with the configuration of LEDs on the heat sink. The test LEDs (RGB and phosphor-converted white) were mounted on a 6" diameter, 1/4" thick round white painted aluminum heat sink using double-sided thermal tape. The mounting positions of the LEDs were alternated such that no two similar colors were adjacent to one another. The mixed-color LED system consisted of three each red, green, and blue LEDs, and the PC white LED system of nine PC-white LEDs.

Wired in series by color in groups of three, each group of LEDs was driven off an individual power supply. In line of the circuit was an IRL630 Power MOSFET connected to a function generator to control the PWM switching operation. For the continuous current scheme, the power supplies were set for constant current operation and the current was adjusted as needed. For the PWM scheme, the power supplies were set for constant voltage operation and the gate of the MOSFET was driven with a modulated square wave at 1 kHz with varying duty cycle. Current measurements were taken across a 1 ohm, 5% tolerance current sense resistor using a digital multimeter.

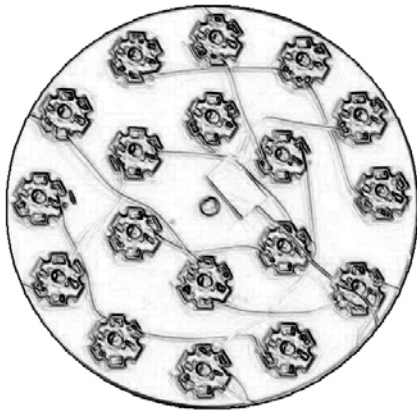


Figure 2(a): Illustration of the LED system.

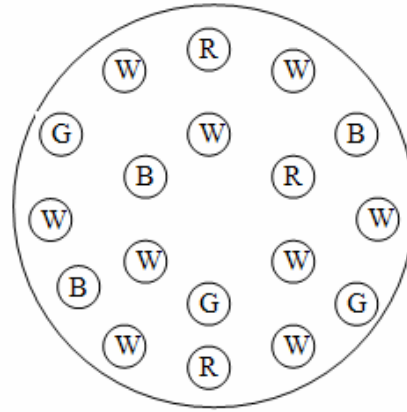


Figure 2(b): Location of LEDs with respect to color for the LED system.

The experimental setup is shown in Figure 3. The LED system was mounted within a six-foot diameter integrating sphere, which acted as the main integrating chamber to spatially mix the light from the individual LEDs. A small, 8-inch diameter satellite sphere was attached to the main sphere. This smaller satellite sphere received incident light from the larger sphere with an accurate cosine response, and provided an orthogonal opening for the spectroradiometer at a 90° angle. Light output measurements were made using a $V(\lambda)$ corrected illuminance meter mounted to the smaller satellite sphere and interfaced with a pico ammeter. A spectroradiometer was aimed at the satellite sphere to record spectral data.

Light output and spectral data were recorded for the PC white LED system under the continuous current dimming scheme to create an initial baseline to be used for the PWM condition and the mixed-color LED system. The PC white system was driven at 10.5 mA (or 3% the total light output) and allowed to stabilize for 10 minutes. Once light output and spectral data were recorded, the current was increased to the next level. The process was repeated for a total of seven current levels (10.5 mA, 17.5 mA, 35 mA, 105 mA, 175 mA, 245 mA, and 350 mA), equating to 3%, 5%, 10%, 30%, 50%, 70%, and 100% light output. Under PWM operation, the duty cycle was adjusted such that the light level matched the equivalent value measured under constant current operation, and the corresponding SPD was measured. The RGB system underwent the same process, only that the ratio of red, green, and blue was initially adjusted to match the white point of the PC white LED system. The current level for the continuous current dimming scheme and duty cycle for the PWM dimming scheme were adjusted so that the PWM conditions produced the same luminous flux as the PC white LED system under continuous current operation. The RGB mixed-color system was adjusted to match 10% reductions in the current level, without regard to matching the light output.

3. RESULTS

The experiment results are illustrated in Figures 4(a) and 4(b). In these figures, the measured chromaticity values are plotted on the 1931 and 1976 CIE chromaticity diagrams. The 1931 CIE x,y diagram is one of the most familiar color diagrams; however, the 1976 U^*V^* is a uniform space, which allows for comparing chromaticity shifts. From these figures it is evident that the chromaticity shift of PC white LEDs, when the light output is dimmed by both dimming methods from 100% to 3%, is very small, less than a 4-step MacAdam ellipse. In comparison, the RGB mixed-color white light system studied in this experiment had large chromaticity shifts. It is also evident that the chromaticity shifts are in different directions for both the PC white and RGB mixed-color white systems when dimmed using continuous current and PWM. This indicates that the mechanisms for chromaticity shift are different for continuous current and PWM.

3.1 PC white LED systems

Figure 5(a) shows the chromaticity shift of the PC white LED system due to continuous current dimming. The normalized SPD for the PC white LED system shown in Figure 5(b) illustrates the relative contribution of the phosphor emission (peak wavelength around 555 nm) increases as the system is dimmed from 100% to 3%. This supports the chromaticity shift toward the yellow at lower currents and indicates that the phosphor is becoming more efficient. One other noticeable effect is that the peak wavelength of the short-wavelength emission (near 460 nm) shifts toward longer wavelengths. At this point it cannot be confirmed whether the phosphor efficiency increase is due to a reduction in heat, or whether the influence of peak wavelength shift of the short-wavelength emission is causing higher absorption efficiency for the phosphor.

Figure 6(a) shows the chromaticity shift of the PC white LED system due to PWM dimming. Here the shift is in the opposite direction, and the magnitude of the shift is less than that under continuous current dimming. The normalized SPD for the PC white LED system shown in Figure 6(b) illustrates that the relative contribution of the phosphor emission decreases as the system is dimmed from 100% to 3%. This explains why the chromaticity shifted toward the blue at lower currents and indicates that the phosphor is becoming less efficient. Unlike continuous current dimming, the peak wavelength position of the short-wavelength emission shifts toward shorter wavelengths. Since the phosphor efficiency decreased when dimmed using PWM, and the position of the short-wavelength emission shifted toward shorter wavelengths, which must be causing the absorption efficiency for the phosphor to reduce.

3.2 RGB mixed color white LED systems

Figure 7(a) shows the chromaticity shift of the RGB mixed-color white LED system due to continuous current dimming. The normalized SPD shown in Figure 7(b) illustrates that the relative contribution of the green emission (peak wavelength around 525 nm) increases and shifts toward longer wavelengths, and the red emission (peak wavelength around 620 nm) decreases and shifts toward shorter wavelengths as the system is dimmed from 100% to 3%. This supports the chromaticity shift towards the green at lower currents.

Figure 8(a) shows the chromaticity shift of the RGB mixed-color white LED system due to PWM dimming. Here the shift is in the opposite direction, and the magnitude of the shift is less than that under continuous current dimming. The normalized SPD for the RGB mixed-color white LED system shown in Figure 8(b) illustrates the relative contribution of the RGB emission as the system is dimmed from 100% to 3%. The relative contributions of both red and green emissions decrease with decreasing current, and the peak wavelengths of both shift toward longer wavelengths. This explains why the chromaticity shifted toward the red-amber region at lower currents.

4. DISCUSSION

Both dimming schemes provided small chromaticity shifts for PC white LED systems, with the PWM performing slightly better than the continuous current dimming scheme. The mixed-color system suffered large chromaticity shifts, regardless of the dimming scheme used. An active optical feedback scheme could be implemented for the mixed-color LED system to control the red component PWM operation and to confine the chromaticity shift within a 4-step MacAdam ellipse. Control of both the red and green components under continuous current dimming could also be beneficial, though more complicated and expensive than a PWM dimming solution.

This study has demonstrated the behavior of white light LED systems and the importance dimming schemes have on maintaining unnoticeable color differences between systems. Unfortunately, these results cannot be extrapolated to every LED package available, since the type of behavior reported could be limited to this package. Nevertheless, this study begins to identify the importance of dimming schemes on white LED lighting systems.

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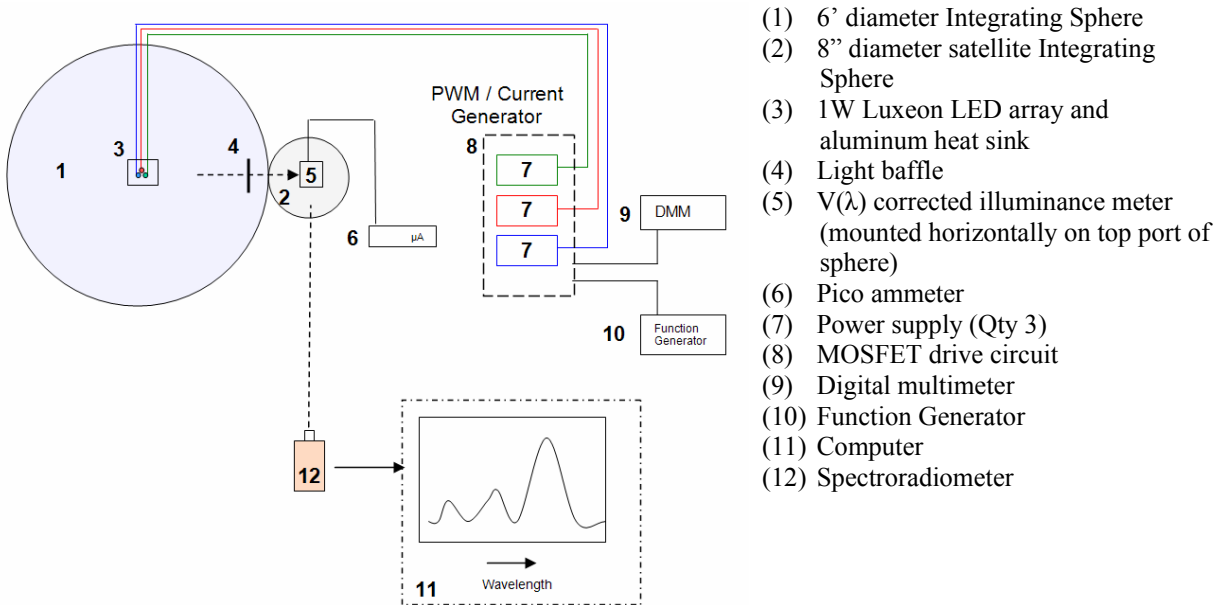
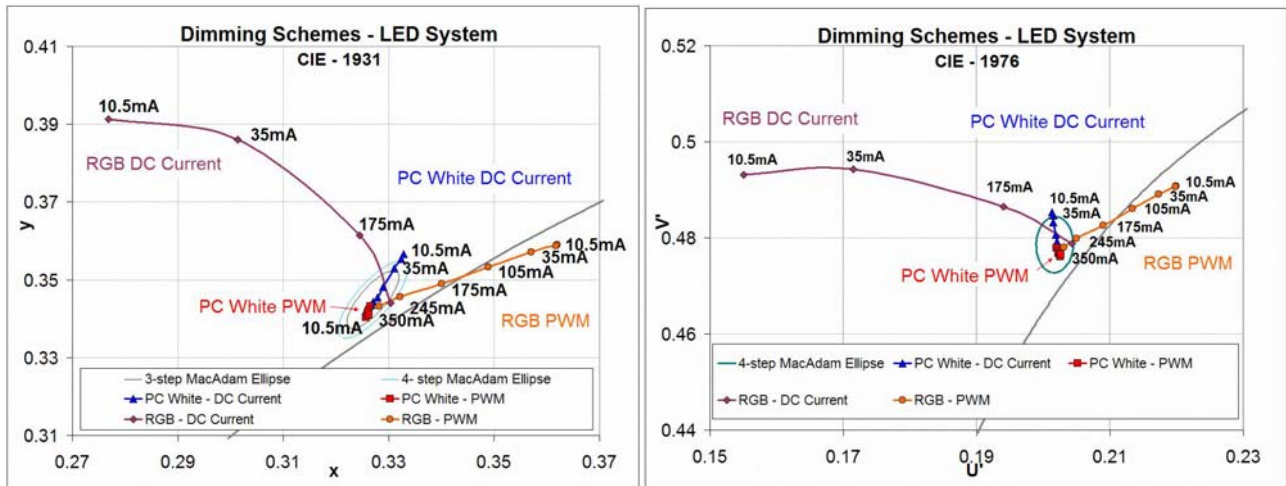


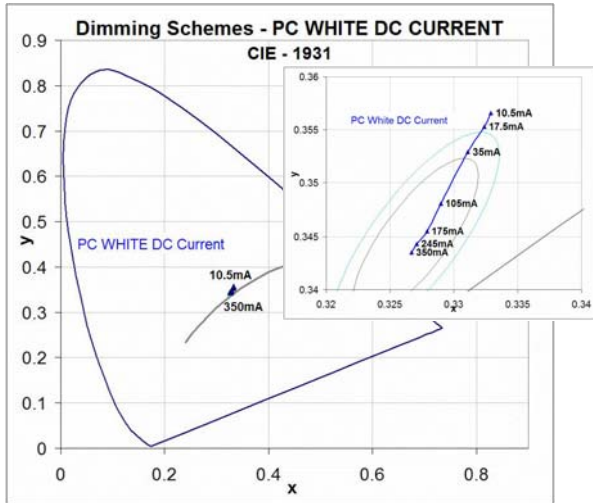
Figure 3: Schematic of experimental setup.



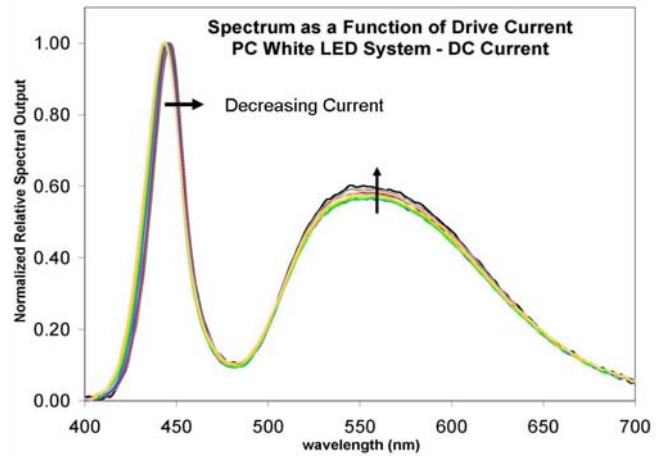
(a)

(b)

Figure 4: Results from PC white and mixed-color LED systems under continuous current and PWM dimming schemes: (a) CIE 1931 (x,y) coordinate system and (b) CIE 1976 (U',V') coordinate system.

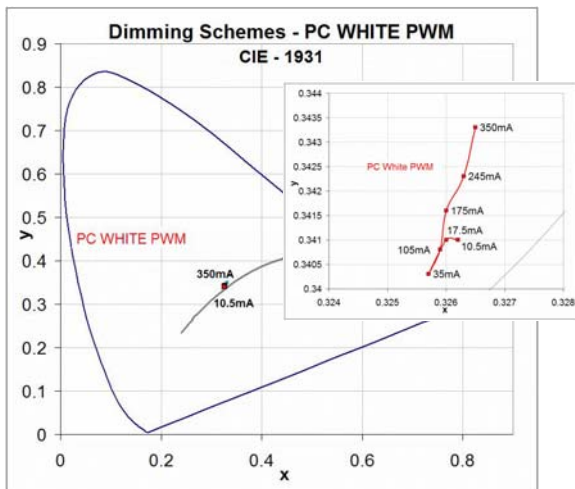


(a)

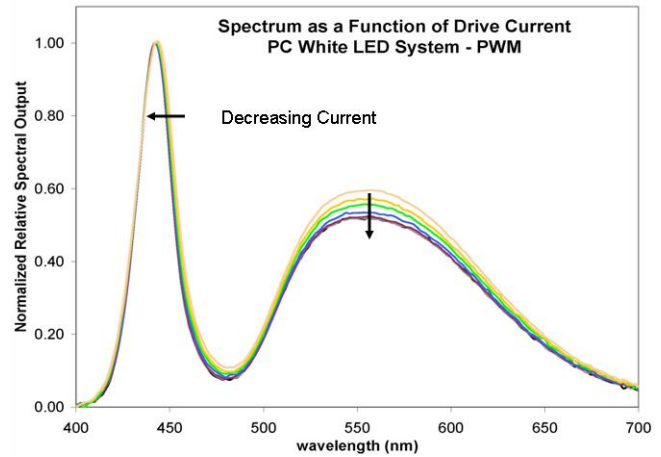


(b)

Figure 5: Continuous current dimming scheme for PC white LED system: (a) chromaticity shift and (b) SPD.

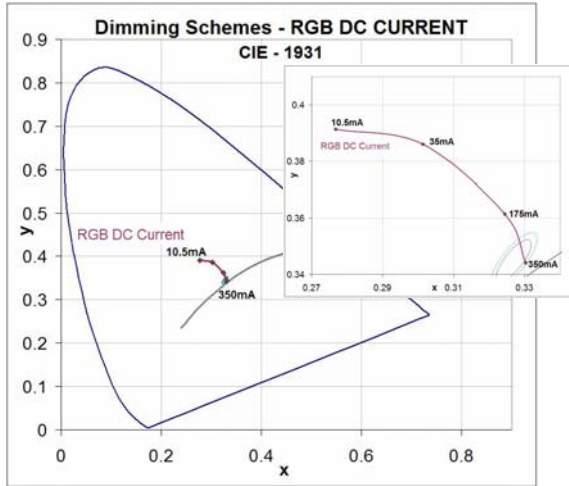


(a)

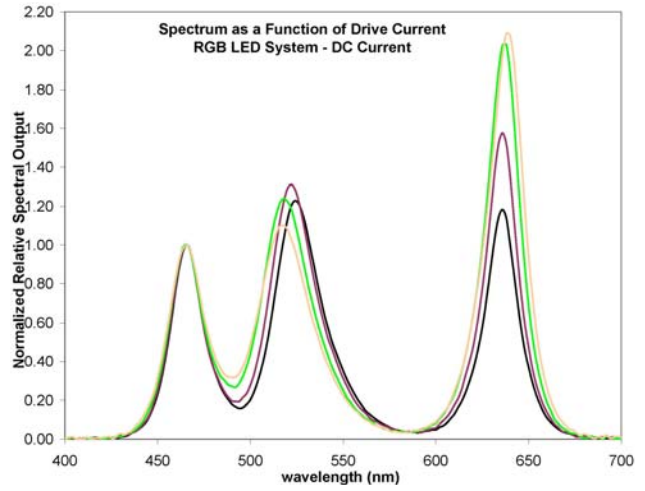


(b)

Figure 6: PWM scheme for PC white LED system: (a) chromaticity shift and (b) SPD.

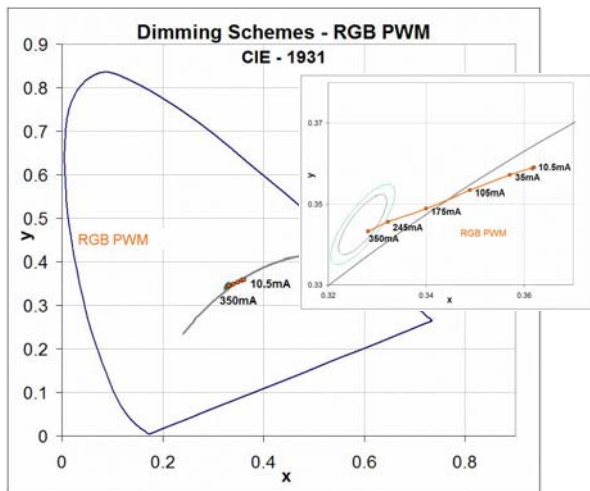


(a)

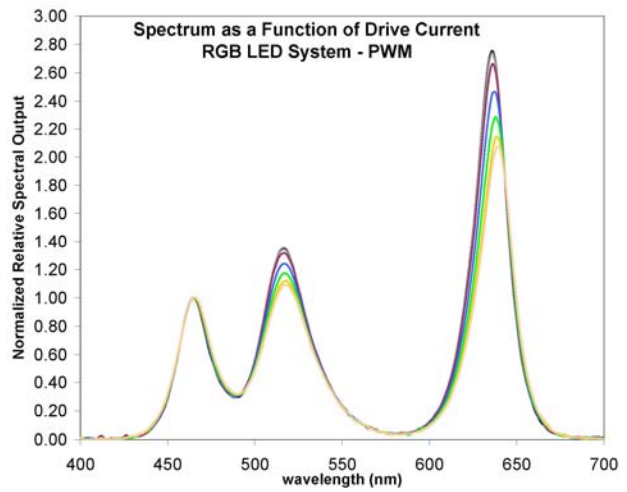


(b)

Figure 7: Continuous current dimming scheme for mixed-color LED system: (a) chromaticity shift and (b) SPD.



(a)



(b)

Figure 8: PWM dimming scheme for mixed-color LED system: (a) chromaticity shift and (b) SPD.