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Color tunable light-emitting diodes with modified pulse-width modulation

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In this study, a color tunable light source, operated by a modified pulse width modulation method, is investigated. By utilizing this method along with anti-parallel connected discrete light-emitting diodes (LEDs) and two electrical terminals, a wide range of the chromaticity coordinates is attained and varied by electrical control. Using the combination of a blue LED and a phosphor-converted yellow LED (blue LED plus yellow phosphor), the chromaticity range is varied by electrical control from pure blue to pure yellow. In addition, using the modified pulse-width modulation method and a combination of white and red LEDs, white light with correlated color temperatures ranging from 5000 K to 2000 K is demonstrated.

1 Introduction Color tunable and efficient light-emitting diodes (LEDs) are attractive for numerous illumination applications [1]. However, it is difficult to simultaneously achieve both of these qualities, that is, color tunability and high efficiency, with current technologies. Current approaches have relied on vertically stacked GaInN quantum wells (with different quantum well thickness or In content) sandwiched in a GaN-based p–n junction diode [2] or laterally distributed GaInN quantum wells (with different quantum well thickness) grown on different facets of GaN [3]. However, because the relative amounts of current that flow through each quantum well determine the final color coordinates of the device, it is difficult to achieve the desired real-time controllability of the chromaticity. As an alternative approach, two different colored LEDs with a current-distribution-control unit can be used to achieve color tunability [4]. However, in order to distribute the current between the two LEDs and render the desired coordinates, more than two electrical terminals are necessary with conventional approaches. In addition, adding electrical terminals to a lighting system complicates the circuitry and the fabrication process.

Pulse width modulation (PWM) is widely used to regulate the intensity of light sources in applications such as dimmable backlighting units for liquid crystal displays [5]. Whereas conventional PWM [6, 7] generally switches between zero and a positive voltage, the modified PWM [8] is switched between a negative voltage and a positive voltage, as shown in Fig. 1. By using the modified PWM at high frequency, an efficiency improvement of GaInN LED was reported [8]. The authors hypothesized that the efficiency improvement was due to enhanced redistribution of electron–hole pairs by oscillation of the negative bias. Though the reverse bias induced alternately might influence the device reliability, the modified PWM can provide additional functionality to operate LEDs because many parameters such as positive and negative voltages, frequency, pulse width, and the duty ratio can be independently controlled, which is not possible with typical continuous wave (cw) LED operation. In this study, a color tunable LED system is developed by using two LEDs emitting at two different wavelengths. Color tunability can be realized by changing the typical cw operation of LEDs to the modified PWM operation and by utilizing only two electrical termi-

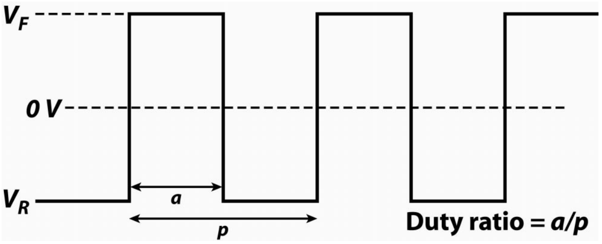

Figure 1 Schematic of the modified pulse width modulation. The duty ratio is *a*/*p* where *a* is the pulse width and *p* is the pulse period.

nals in the system by connecting two discrete LEDs in an anti-parallel way.

2 Device structure and fabrication methods

A schematic diagram showing how the LED chips are interconnected via metal wires is illustrated in Fig. 2(a). Both LED chips make an anti-parallel connection while sharing the two terminals. In this configuration, each power load of the positive and negative directions of the modified PWM can be applied alternately to independently operate each of the two chips. That means the relative amount of the electrical power of the two chips is determined by directly changing the duty ratio of the modified PWM. As an additional advantage of the anti-parallel connection of the two chips, it is intrinsically robust against electrostatic damage without using a separate device (i.e. an additional Zener diode), because the anti-parallel circuit allows unexpected electrostatic charges to be easily dissipated.

As shown in Fig. 2(b), two different configurations were used for dichromatic light sources. A Type I configuration has a blue LED (200 × 600 μm^2) and a phosphor-converted yellow LED (200 × 600 μm^2). The phosphor-converted yellow LED was made by applying a thick coating of yellow YAG:Ce phosphor on a blue LED. A Type II configuration has a white LED (200 × 600 μm^2), correlated color temperature (CCT) of 5000 K, which was also made by a combination of a blue LED and yellow phosphor, and a red LED (600 × 600 μm^2). The blue LEDs having GaInN/GaN multiple quantum wells were designed for light emission at 460 nm and grown on *c*-faced sapphire substrate. Commercially available AlGaInP-based red LEDs with a peak emission at 600 nm were used. After wiring to electrical terminals, silicone resin was used to fill the cavities and to provide protection from unintentional mechanical damages.

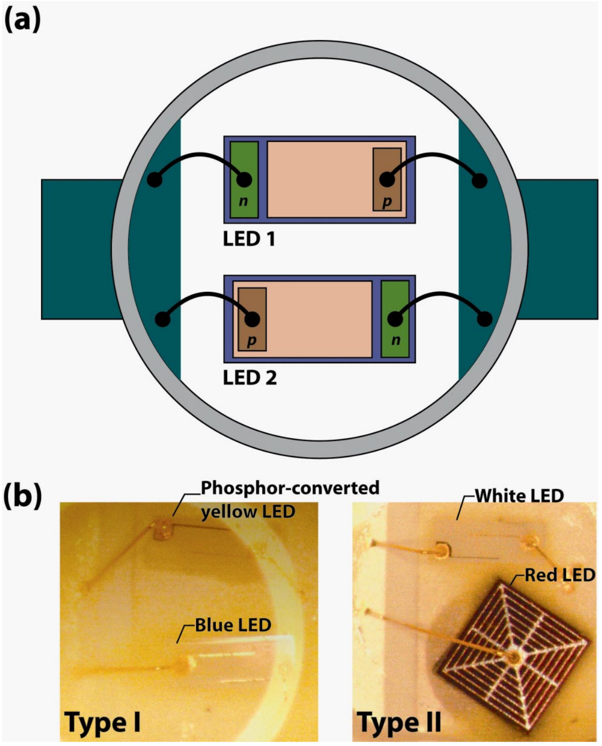

Figure 2 (online colour at: www.pss-rapid.com) (a) Schematic diagram showing LED chips interconnected via metal wires. The LED chips are connected in an anti-parallel way and they share two terminals. (b) Optical microscope images of the Type I and Type II configuration.

3 Color tunability of LEDs Firstly, the electrically tunable color properties of the dichromatic light sources were investigated. The anti-parallel connected LEDs were tested at a frequency of 1 kHz (i.e. pulse period of 1 ms) and positive (V_F) and negative (V_R) voltages at a current of 10 mA to each LED. The voltages for the 10 mA current were 3.1 V for the blue LED and 1.8 V for the red LED. Therefore, V_F and V_R were both set to 3.1 V in the Type I configuration and the duty ratio was changed to balance the power between the two devices. For the Type II configuration, V_F = 3.1 V for the white LED and V_R = 1.8 V for the red LED were applied. The *Commission Internationale de l'Eclairage* (CIE) 1931 chromaticities [9] of the LEDs were measured using an integrating sphere connected to a spectrometer. The color coordinates of the dichromatic light source are given by:

$$\mathrm{CIE}\,(x,y) = F(a/p)\,\mathrm{CIE}_{\mathrm{LED1}}(x,y) + (1-a/p)\,\mathrm{CIE}_{\mathrm{LED2}}(x,y)\,, \tag{1}$$

where F is a weighting factor, a/p is the duty ratio of the electrical driver provided to one LED, and $\mathrm{CIE}_{\mathrm{LED1}}(x, y)$ and $\mathrm{CIE}_{\mathrm{LED2}}(x, y)$ are the color coordinates for each individual LED. The weighting factor, F, is determined by the relative luminous intensity of the light sources at $\mathrm{CIE}_{\mathrm{LED1}}(x, y)$ and $\mathrm{CIE}_{\mathrm{LED2}}(x, y)$. When the duty ratio of the pulse generator was changed from 0.1% to 99%, the chromaticity coordinates of Type I varied between (0.14, 0.06) and (0.49, 0.49), which is almost pure blue to pure yellow. For example, when the duty ratio was 0.1%, the duration of the positive pulse was 0.1% of the total time, whereas a negative pulse was induced for the remainder of the time (99.9%). Figure 3 (blue line) shows the CIE coordinates of

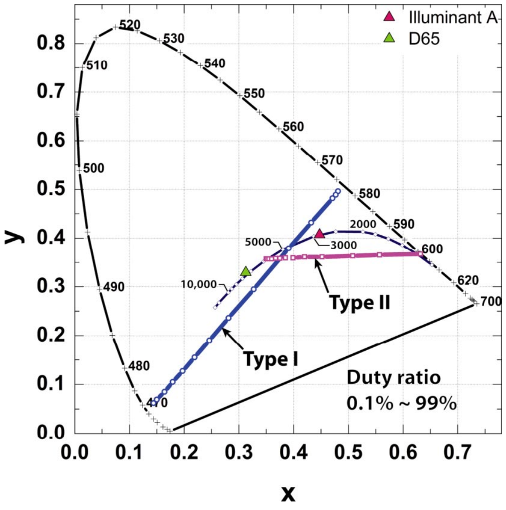

Figure 3 (online colour at: www.pss-rapid.com) CIE (x, y) coordinate system with Type I (blue line) and Type II (red line) devices, as well as the spectral and Planckian loci.

the Type I dichromatic light source as well as the spectral and Planckian loci. In the middle of the variation, a white color can be made within the CCT range of 6000 K to 3000 K. In the case of Type II shown in Fig. 3 (red line), the chromaticity coordinates vary between (0.35, 0.35) and (0.63, 0.37) at the same variation of the duty ratio; the chromaticity point follows a straight line and is somewhat below the Plackian locus. Starting from a CCT of 5000 K, a very low CCT of 2000 K can be reached with this configuration. Thus it follows that a very broad range of color tunability can be obtained with the anti-parallel configuration by changing only the duty ratio.

Figure 4 shows a gradual change of the Type I emission spectrum as the duty ratio is increased. The peak wavelength of 460 nm is from the blue LED and the wide peak near 550 nm is from the yellow saturated LED. At a duty ratio of 0.1%, a nearly blue emission is dominant with yellow emission being negligibly small. However, when the duty ratio is increased, the situation becomes reversed, resulting in decreased blue emission and increased yellow emission. Finally, yellow emission is dominant with a very weak blue peak at a duty ratio of 99%. A similar trend of the spectrum was also found for Type II with white and red emissions (not shown here).

4 Conclusion We investigated an electrically color-tunable light source by using the modified PWM method.

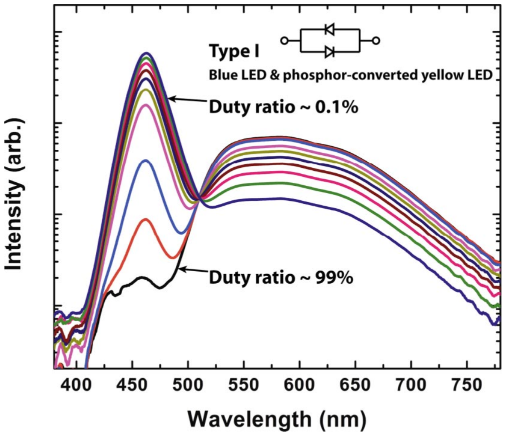

Figure 4 (online colour at: www.pss-rapid.com) Emission spectra from the Type I light source as a function of the duty ratio.

By utilizing two discrete LEDs connected anti-parallel to the electrical terminals, a wide range of the chromaticity coordinates can be obtained. With a large number of possible combinations of dichromatic two-component light sources, versatile color expressions are shown to be possible by the modified PWM.

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