Spectral and Luminous Efficacy Change of High-power LEDs Under Different Dimming Methods

Yimin Gu, Nadarajah Narendran, Tianming Dong and Huiying Wu

Lighting Research Center
Rensselaer Polytechnic Institute, Troy, NY 12180
www.lrc.rpi.edu

Gu, Y., N. Narendran, T. Dong, and H. Wu. 2006. Spectral and luminous efficacy change of high-power LEDs under different dimming methods. *Sixth International Conference on Solid State Lighting, Proceedings of SPIE* 6337, 63370J.

Spectral and Luminous Efficacy Change of High-power LEDs Under Different Dimming Methods

Yimin Gu, Nadarajah Narendran, Tianming Dong and Huiying Wu
Lighting Research Center, Rensselaer Polytechnic Institute, 21 Union St., Troy, NY, 12180 USA

ABSTRACT

Dimming is an important and necessary feature for light sources used in general lighting applications. An experimental study was conducted to quantify the spectral and luminous efficacy change of high-power colored and pc-white LEDs under continuous current reduction (CCR) and pulse-width modulation (PWM) dimming schemes. For InGaN-based blue, green, and pc-white LEDs, the peak wavelength shifts were in opposite directions for the two dimming schemes. The peak wavelength showed a blue shift with increased current, most likely due to band filling and QCSE dominated effects. InGaN LEDs exhibited red shifts with increased duty cycle, which is dominated by junction heat. AlInGaP red LEDs show mainly thermal-induced red shift with increased current or duty cycle. In addition, the luminous efficacy was always higher for the CCR dimming scheme at dimmed levels, irrespective of the LED type.

Keywords: Light-emitting diodes (LEDs), white LEDs, mixed-color white LEDs, pulse-width modulation (PWM), continuous current reduction (CCR), peak wavelength shift, luminous efficacy

1. INTRODUCTION

High-power LEDs for lighting applications have generated much enthusiasm in the industry because of the potential energy savings and reduced maintenance cost due to long lifetimes compared with traditional light sources. Dimming is an important feature that is needed in many lighting applications. However, it is not desirable for a dimmed light source to have a perceivable chromaticity shift towards certain hues or lower luminous efficacy. Two schemes are widely used in the industry for LED dimming: decreasing the forward current (continuous current reduction, CCR), or changing the duty cycle by pulse-width modulation (PWM). In general, PWM is more popular in the industry for dimming LEDs because of its wide dimming range and the linear relationship between the light output and the duty cycle.

The two common white LED types include phosphor converted (PC) and mixed color (MC). Studies have shown that mixed-color white LED systems without active feedback control suffer from highly perceivable chromaticity shifts because of the greatly different performance that each type of LED has with regards to heat at the p-n junction and time dependent flux change.[1,2] Contrary to the common belief that PWM dimming methods exhibit low chromaticity shift, RGB mixed-color white LED systems exhibit large chromaticity shifts when dimmed using both CCR and PWM dimming schemes.[1] However, that same study showed the chromaticity shift for pc-white LEDs was small under both dimming schemes.[1] In addition, they reported opposing peak wavelength shifts for InGaN-based green, blue, and white LEDs under PWM and CCR dimming methods: red-shift under continuous current dimming and blue-shift using the PWM method.[1]

To the best of our knowledge, none of the past studies have quantified spectrum shift and the luminous efficacy change of different colored and white LEDs at different dimmed levels. Therefore, the goal of this study was to quantify the spectral and luminous efficacy change of colored and pc-white LEDs under continuous current dimming and PWM dimming schemes.

According to other studies, both current density and heat at the p-n junction can affect the spectrum.[3-6] Studies have suggested that the red-shift of the InGaN-based LEDs under decreasing continuous current is caused by band filling and quantum-confined stark effect (QCSE).[7,8]

guyim@rpi.edu; phone 1 518 687-7100; www.lrc.rpi.edu

2. EXPERIMENTS

Four types of high-power LEDs were used in this study, one each of red, green, blue, and white from a single manufacturer. These LEDs were compared with similar LEDs from two other manufacturers. Additionally, the different mechanisms for spectrum shift under CCR and PWM dimming were examined.

2.1 Experimental setup

Test LEDs were suspended at the center of a thermal chamber, one LED at a time. The chamber was an 8 in. by 8 in. (20.32 cm by 20.32 cm) square wooden box. The chamber was designed to keep the temperature surrounding the LED constant and to act as a light-integrating box for measuring light output. A USB2000 spectrometer from Ocean Optics was used to measure the spectrum. The spectrometer detector was attached to the center of the left chamber panel. A small white baffle placed over the detector allowed only the reflected light to reach the detector. A heater was attached to a raised aluminum plate with a matte-white cover that sat on the chamber floor. A resistance temperature detector placed on top of the baffle measured the chamber's ambient temperature and controlled the heater through a temperature controller. The temperature inside the box remained within ± 1°C.

2.2 Experimental conditions

An electronic circuit was built to power the LED and to measure its voltage and current. Each LED was driven at seven continuous current conditions of 350 mA, 280 mA, 210 mA, 140 mA, 70 mA, 35 mA, and 17.5 mA, equating to 100%, 80%, 60%, 40%, 20%, 10%, and 5% of the 350 mA nominal current. Under the PWM operation, the LED's light output was changed by adjusting the duty cycle to 100%, 80%, 60%, 40%, 20%, 10%, and 5%. The frequency used for the PWM operation was 120 Hz. A pilot study showed that frequencies above 100 Hz did not affect system performance in terms of light output, peak wavelength shift, and power. The temperature inside the chamber was maintained at 30°C. LED voltage and the light output spectral data were recorded at each condition. Using these data, the corresponding luminous efficacy and peak wavelength were determined.

3. RESULTS

3.1 Peak wavelength shift

During the dimming experiment, the light output and junction temperature of each LED decreased with decreasing current (CCR) or duty cycle (PWM). Fig. 1 illustrates the peak wavelength shift as a function of current level or duty cycle for all four LEDs from manufacturer A. The PC-white LEDs have peaks for the blue and down-converted yellow portions. However, the peak wavelength shift for the yellow peak barely changed. Therefore, only the blue peak wavelength was considered. For the AlInGaP red LED (Fig. 1a), the peak wavelength decreased, or blue shifted, with reduced current or duty cycle, and these shifts were very similar. For the InGaN-based green (Fig. 1b), blue (Fig. 1c), and white LEDs (Fig. 1d), the peak wavelength increased with reduced current and decreased with reduced duty cycle. The opposing peak wavelength shifts between the two dimming methods are similar to what Dyble et al. observed in their study.[1] Also for InGaN LEDs, the amount of peak wavelength shift increased at longer wavelengths. At a 5% dimming level, the peak wavelength difference between the two dimming methods was larger than 10 nm for the green LED.

Results for similar LEDs from two other manufacturers showed similar trends. Fig. 2 shows the peak wavelength shifts under different dimming levels for the twelve LEDs. The peak wavelengths of each individual LED at each dimming level were compared to the LED's peak wavelength at nominal current. Again, the AlInGaP red LEDs from manufacturers B and C exhibited blue shifts with decreased current or duty cycle. The InGaN-based blue, green, and white LEDs showed the opposite peak wavelength shifts depending on the dimming scheme. According to past studies, the blue shift with increased current for InGaN LEDs is most likely due to band filling and QCSE caused by indium (In) fluctuation and the thickness of the InGaN active layer.[7-9] Though blue and green LEDs are both InGaN-based, the green LEDs have more indium composition, and therefore higher indium fluctuation within the InGaN quantum well.[9] This higher indium fluctuation causes the green LED to have a larger blue shift at higher CC levels.[9]

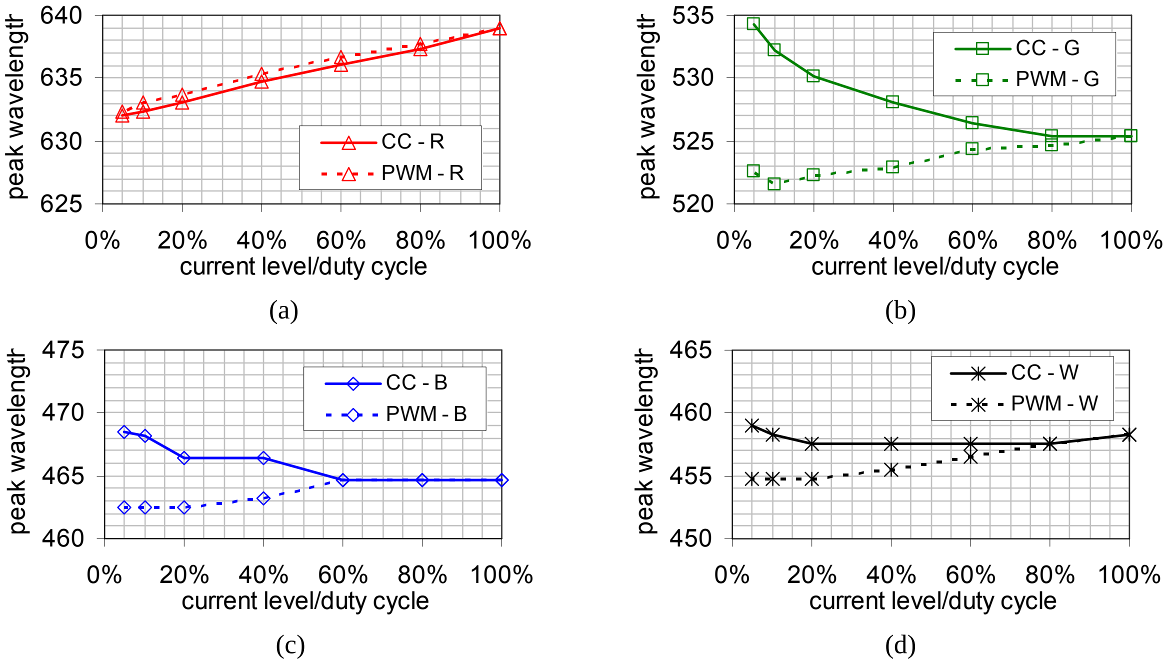
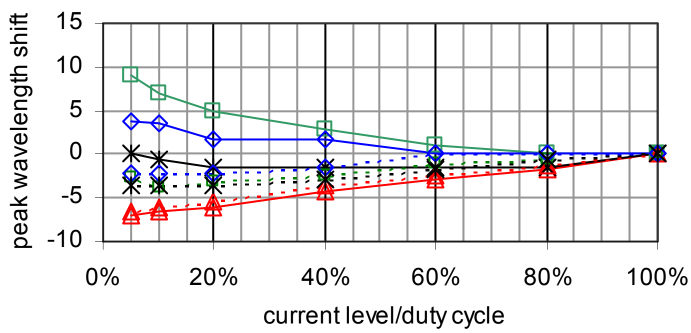
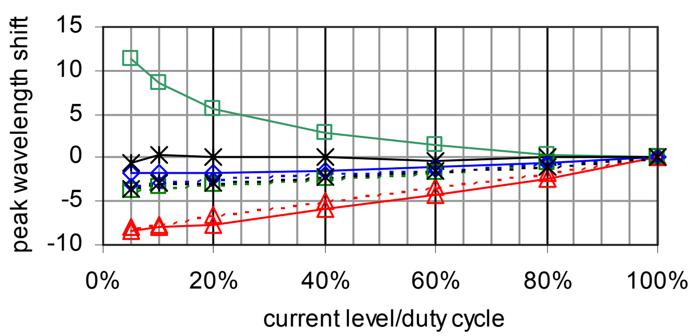


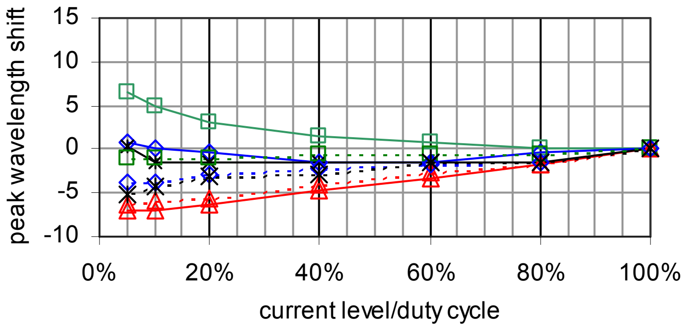
Fig. 1. Peak wavelength shift as a function of current level or duty cycle for (a) red, (b) green, (c) blue, and (d) pc-white LEDs from manufacturer A.



(a) Manufacturer A



(b) Manufacturer B



(c) Manufacturer C

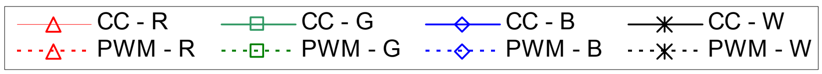
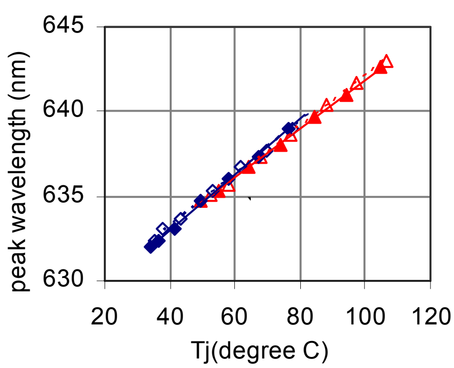


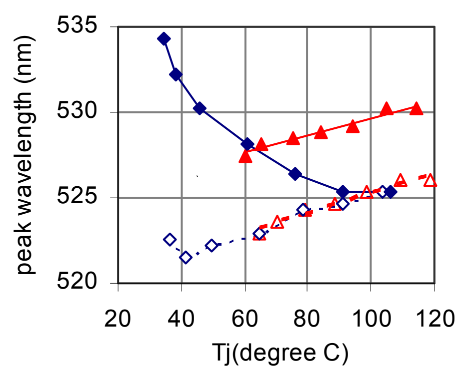
Fig. 2. Peak wavelength shift as a function of current level or duty cycle for LEDs from manufacturers A, B, and C.

The red shift observed during increased duty cycle could be caused by heat at the junction. To verify this hypothesis, a separate temperature test was conducted to determine how temperature influences the spectrum of different LEDs when the current influence is eliminated. The LED was maintained at a constant dimming condition: 140 mA (40% of the nominal current) for continuous current operation or 40% duty cycle for PWM operation. The temperature inside the chamber was changed from 35°C to 85°C at 10°C intervals. The tip of a J-type thin wire thermocouple was soldered to the cathode pin of the LED. Cathode pin temperature, LED voltage, and the light output spectral data were recorded at each condition. The junction temperature of the test LED could be estimated from the cathode pin temperature, the power dissipated at the p-n junction, and the thermal resistance coefficient from the LED junction to solder point.[3]

For the temperature test, the light output decreased, junction temperature increased, and the spectrum shifted to longer wavelengths for all LEDs with elevated ambient temperatures. Fig. 3 illustrates the peak wavelength as a function of junction temperature for red and green LEDs from manufacturer A. Each plot shows the four test conditions: constant ambient temperature with changing continuous current or duty cycle, or constant continuous current or duty cycle with changing ambient temperature. The peak wavelength shift for the red LED was always proportional to the change in junction temperature (Fig. 3a), regardless of how the heat was generated at the junction (either by increasing the ambient temperature or the drive current/duty cycle). This agrees with results from the Hong et al. study.[5] However, for the green LED (Fig. 3b), the peak wavelength under PWM operation was always proportional to the junction temperature, irrespective of the source that changed the junction temperature. Similar results were observed for other InGaN LEDs. Therefore, we can conclude that there are different mechanisms contributing to peak wavelength shift for CCR and PWM dimming. Band filling and QCSE seem to dominate the spectrum shift for CCR operation, while heat becomes the main contributor to spectrum shift for PWM operation.



(a)



(b)

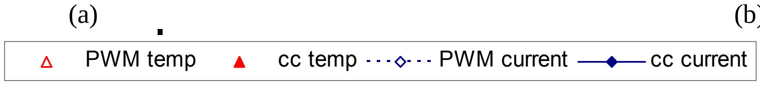


Fig. 3. Peak wavelength shift as a function of junction temperature for (a) red and (b) green LEDs from manufacturer A.

3.2 Luminous efficacy

The luminous efficacy of a light source can be affected by several factors: the radiant energy output of the light source, the power dissipated at the p-n junction, or the spectral shift. Depending on the peak wavelength position, a small spectral shift can lead to a large change in the luminous flux. Luminous flux is obtained by weighting the spectral power distribution by the luminous spectral power sensitivity curve of the human vision, V(λ), peaking at 555 nm. For example, the green LED from manufacturer A has its peak wavelength at 525 nm at nominal drive current. This peak position is located on the steep slope of the V(λ) curve on the shorter wavelength side. The peak wavelength shifts toward the peak of the V(λ) curve under CCR dimming, and away from the peak of the V(λ) curve under PWM dimming. Therefore, for the green LED from manufacturer A, the 10 nm peak wavelength difference at the 5% current level and the 5% duty cycle can cause an approximate 15% difference in luminous flux if the amplitude of the spectra is kept the same.

Fig. 4 shows the relative light output over power for both red and green LEDs from manufacturer A under both dimming methods. During dimming, input power and light output decreased. However, under CCR operation, the LEDs showed a faster decrease rate for input power compared with PWM. Therefore, to reach the same light level, PWM dimming demands more power than CCR dimming; in other words, efficacy is higher for CCR dimming at all dimming levels. Additionally, the rate of light output reduction is always less than that of input power with CCR operation, except at the lower dimming range. Hence, LED efficacy increases when dimmed with CCR operation and decreases with PWM operation. Other LEDs showed similar changes with the two dimming methods.

Fig. 5 illustrates luminous efficacy as a function of current level or duty cycle for all LEDs under the two dimming methods. The plotted efficacies were normalized to each LED’s efficacy at 350 mA nominal current. Under CCR dimming, the efficacies of all LEDs increased with decreasing current and junction temperature. However, with a further decrease in current (less than 35 mA), a reduction of the efficacy was observed. The efficacy change was in the opposite direction for the PWM dimming. The efficacy stayed constant for a while and then decreased with reduced duty cycle. Fig. 6 compares the relative efficacies of the four LEDs from manufacturer A at 70 mA continuous current level or 20% duty cycle. The relative efficacy difference between CCR and PWM can be higher than 100%.

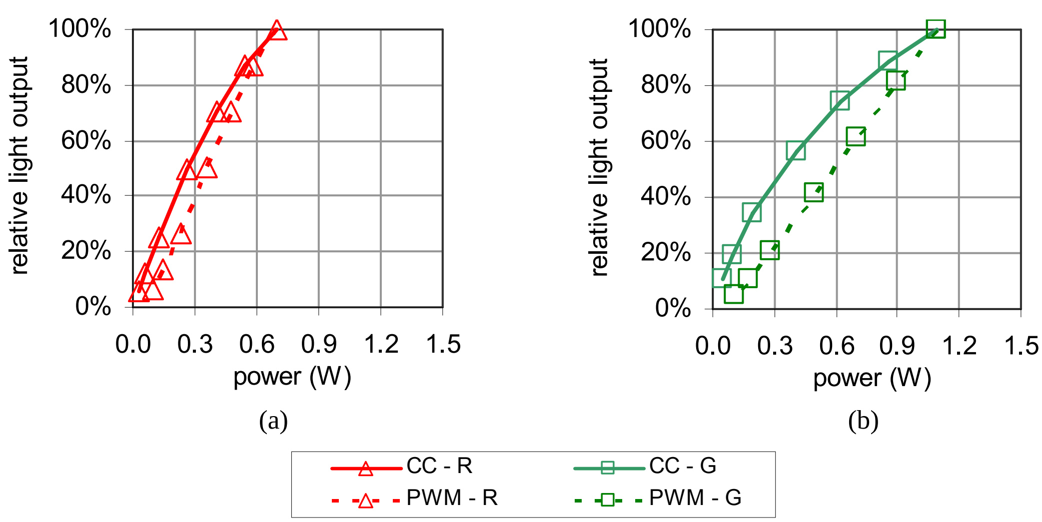


Fig. 4. Relative light output as a function of power for (a) red and (b) green LEDs from manufacturer A.

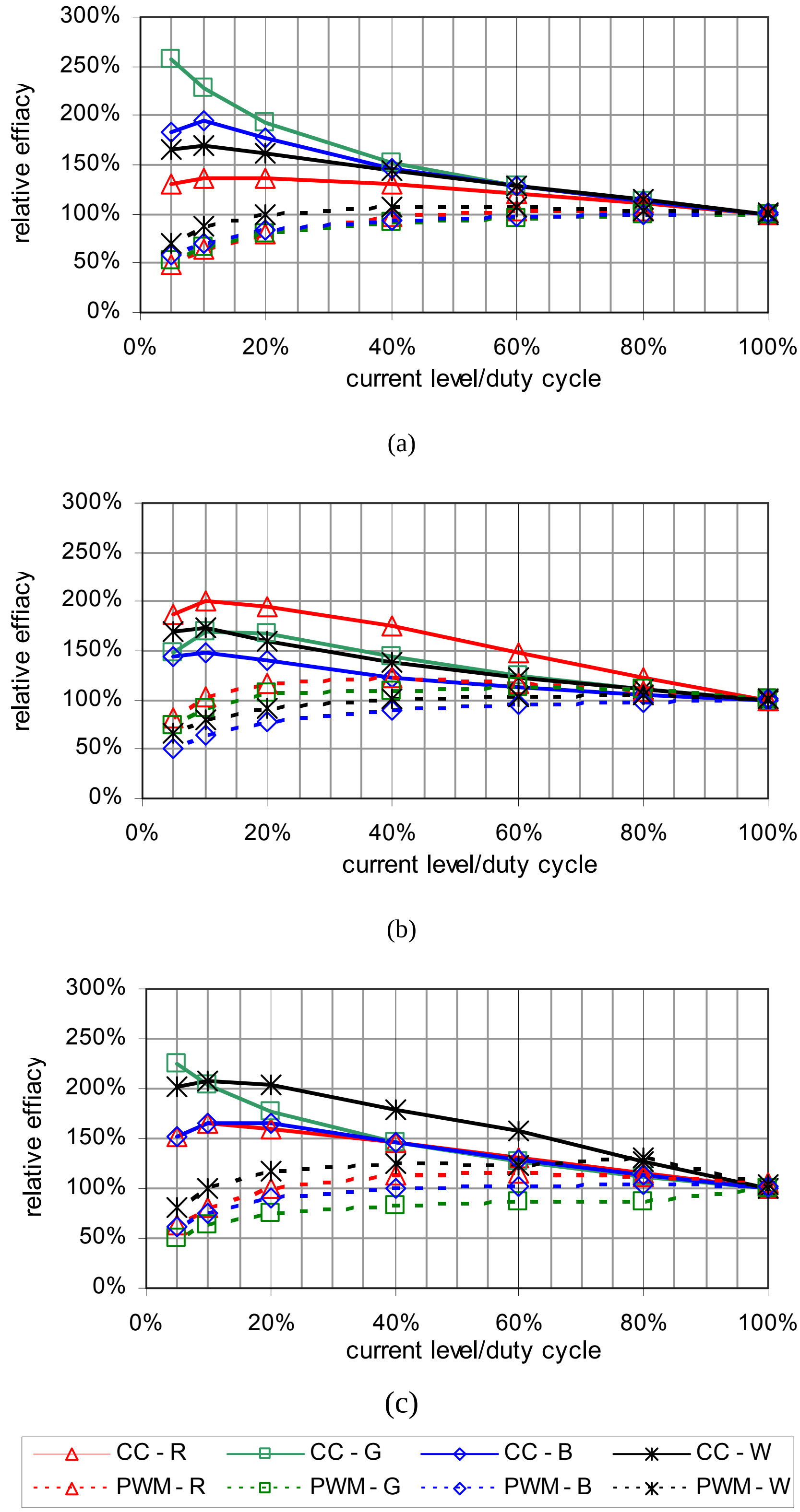


Fig. 5. Relative luminous efficacy as a function of junction temperature for red, green, blue, and white LEDs from manufacturer (a) A, (b) B, and (c) C.

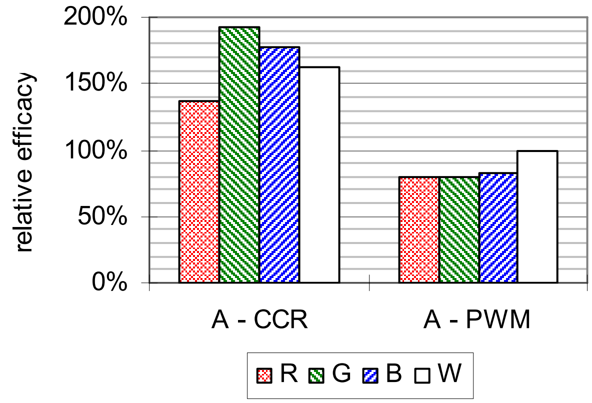


Fig. 6. Relative luminous efficacy for red, green, blue, and white LEDs at 20% current level or duty cycle from manufacturer A.

4. SUMMARY

An experimental study was conducted to quantify the spectral and luminous efficacy change of high-power colored and pc-white LEDs under continuous current dimming and PWM dimming schemes. For InGaN-based blue, green, and pc-white LEDs, the peak wavelength shifts were in opposite directions for the two dimming schemes. The peak wavelength showed a blue shift with increased current, most likely due to band filling and QCSE dominated effects. InGaN LEDs exhibited red shifts with increased duty cycle, which is dominated by junction heat. AlInGaP red LEDs show mainly thermal-induced red shift with increased current or duty cycle. In addition, the luminous efficacy was always higher for CCR dimming at dimmed levels, irrespective of the LED type.

From these results, we can expect a large chromaticity shift from mixed-color white LED systems during dimming. Hence, it is necessary to use electronic feedback control to minimize the chromaticity shift of mixed-color systems.[2]

ACKNOWLEDGMENTS

The authors thank the Alliance for Solid-State Illumination Systems and Technologies (ASSIST) for its financial support of this study. The authors would like to thank Terry Klein of the Lighting Research Center for his valuable support. Jennifer Taylor of the Lighting Research Center is also thanked for her valuable help in preparing this manuscript.

REFERENCES

1. M. Dyble, N. Narendran, A. Bierman, and T. Klein, "Impact of dimming white LEDs: Chromaticity shifts due to different dimming methods," *SPIE Proceedings* 5941, 291-299 (2005).
2. S. Muthu, F. Schuurmans, and M. Pashley, "Red, green, and blue LED based white light generation: Issues and control," *37th Annual IEEE-IAS meeting* Vol. 2, 327-333 (2002).
3. Y. Gu and N. Narendran, "A non-contact method for determining junction temperature of phosphor-converted white LEDs," *SPIE Proceedings* 5187, 107-114 (2004).
4. R. Mueller-Mach, G.O. Mueller, M.R. Krames, and T. Trottier, "High-power phosphor-converted light-emitting diodes based on III-nitrides," *IEEE J. Sel. Topics Quantum Electron.* 8(2), 339-345 (2002).
5. E. Hong and N. Narendran, "A method for projecting useful life of LED lighting systems," *SPIE Proceedings* 5187, 93-99 (2004).
6. S. Nakamura, T. Mukai, and M. Senoh, "High-brightness InGaN/AlGaN double-heterostructure blue-green-light-emitting diodes," *J. Appl. Phys.* 76(12), 8189-8191 (1994).
7. S. Nakamura, "The role of structural imperfections in InGaN-based blue light-emitting diodes and laser diodes," *Science* 281, 956-961 (1998).
8. T. Mukai, M. Yamada, and S. Nakamura, "InGaN-based UV/blue/green/amber/red LEDs," *SPIE Proceedings 3621,* 2-13 (1999).
9. A.Y. Kim et al., "Performance of high-power AlInGaN light emitting diodes," *Phys. Stat. Sol. (a)* 188(1), 15-21 (2001).