Design of highly efficient white LED for the maximal CRI

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Abstract

Phosphor-converted white light emitting diodes (pc-LEDs) are being used as a source of artificial lighting. One of the main goals of artificial lighting is to make objects/images look natural – as they look under the sunlight. The ability of a light source to accurately render the natural color of an object is gauged by the color rendering index (CRI) and a conventional pc-LED has an average CRI– CRI R_a ~ 80 which is not suitable for artificial lighting. In order to fabricate the pc-LEDs for artificial lighting applications, all the CRI points (R_1 – R_{15}) should be above 95. Herein a novel design strategy of an LED package (PKG) is implemented to achieve CRI points ≥ 95 through introducing two blue LEDs and a UV LED in combination with green and red phosphors. The silicone encapsulant, the ratio of the current through the LEDs, and the phosphor ratio were optimized for achieving high efficiency (~ 100 lm/W) as well as all the CRI points above 95. Our re-designed LED PKG with an efficiency of around 100 lm/W would find applications in stadium lighting as well as for ultra-high definition television production where high CRI points are required for the light source.

1. Introduction

Phosphor-converted white light emitting diodes (pc-WLEDs) have emerged as next-generation solid-state lighting technology and is a potential substitute for traditional lighting sources such as incandescent lamps, fluorescent lamps, halogen lamps, and backlights for liquid crystal displays.[1–3] The low power consumption, high luminous efficacy, and environment-friendly characteristics make the pc-WLEDs attractive. The most commonly accepted and commercially available pc-WLEDs are based on the combination of a blue-chip + yellow phosphor or blue-chip + green and red phosphors. Various phosphors have been studied by our group and others and utilized the phosphors for fabricating highly efficient and reliable WLEDs. [4–12] Several strategies have been proposed to enhance the luminous efficacy and stability of the pc-WLEDs.[13–16] However, apart from the high luminous efficacy, accurate color reproduction is also a major requirement when the WLEDs are used as an artificial light source, especially when WLEDs are used for photography and videography. The color rendering index (CRI)– defined by Commission Internationale de l'éclairage (CIE, International Commission on Illumination) is a quantitative measure which provides the ability of a light source to accurately reproduce the color of the object it illuminates.[17,18] The standard CRI points namely R_1-R_8 are derived from CIE 1974 test color samples and usually arithmetical mean of these values – R_a is used to report the ability to reproduce the color accurately. The special CRI points (R_9- R_{15}) that were derived from realistic colors are also used as a color rendering marker. The recommended Ra values depend on the application environment; nevertheless, R_a of > 80 is recommended for most applications. For lighting in stadiums, most of the athletic committees recommend R_a > 90. Even though R_a is used to evaluate the light sources, saturated colors cannot be evaluated accurately in terms of R_a and numerous new methods for color rendition evaluation has been proposed. Among the new methods, technical memorandum (TM-30) developed by Illuminating Engineering Society (IES) uses 99 color samples including saturated colors.[19,20] In the TM-30 standard, fidelity index (R_f), gamut index (R_g), color vector/saturation graphics, hue fidelity indices ($R_{f,hj}$, j = 1 to 16), chroma change by hue indices ($R_{cs,hj}$, j = 1 to 16), skin fidelity index ($R_{f,skin}$) and sample fidelity index ($R_{f,CESi}$, i = 1-99) are used to evaluate a light source. Depending on the application environment, these values vary and are evaluated as per the requirement. It is very important to have a proper color quality with reasonable efficacy suitable for intended applications. Unlike incandescent and fluorescent lamps, the light emitting diodes (LEDs) emit light in a narrow range of wavelengths in the visible spectrum. This unique optical characteristic has offered big potential for LEDs to produce high-quality white light with reasonable luminous efficacy by combining proper inorganic phosphors. The LEDs as a light source are now far beyond from being a promising technology and the market share of the LEDs in the field of general illumination is dramatically increasing due to the low manufacturing cost. Also, applications of LEDs are being extended to new fields such as horticulture, biologically-driven lighting, and lighting for the art exhibition [21–23]. For each application, the requirement varies and the LEDs must be properly evaluated to find the suitability as per the requirement. Rather than fabricating LEDs with CRI R_a > 80 or 90, individual CRI points (R_1- R_{15}) should be evaluated in detail, with respect to the application environment. In this aspect, recently, a combination of two CRI points such as R_a and R_9 of light sources are evaluated and most of the LED manufacturers label R_a and R_9 on the product specifications.

Even if $R_a > 80$, the R_9 values will be low (< 10) for conventional WLEDs consisting of a blue chip and yellow phosphor. This is because R_9 corresponds to the red component and the blue LED and yellow phosphor combination in WLEDs lack red component. Moreover, for ultra-high definition television (UHDTV) production, high CRI points (> 95) of the light source is required. Therefore, conventional wLEDs consisting of a blue LED and yellow phosphor should be replaced with a high CRI LED for such specific applications. However, it is challenging to enhance CRI points and luminous efficacy simultaneously as there is a trade-off between them.[24] In this work, we have re-designed and optimized the LED package with high luminous efficacy and all the CRI points above 95 by introducing a combination of two blue LEDs and a UV LED along with green and red phosphors. Through properly adjusting the current through each LED and optimizing the phosphor ratio we achieved all the CRI R_1 – R_{15} values above 95. The LEDs were compared with the conventional blue LED + yellow phosphor, blue LED + green & red phosphors, and blue LED + blue, yellow, and red phosphors based LEDs. All the LEDs were evaluated using the TM-30-18 standard.

2. Results and Discussions

Figures 1 (a-d) shows the schematic of LEDs fabricated in this study. Figs. 1(d-e) show a newly designed PKG structure of width x length x thickness = 5.0 mm x 5.4 mm x 1.2 mm developed to incorporate three LEDs (one UV and two blue LEDs). The mounting area in which the chips were directly mounted was a circular structure with a diameter of 2 mm and a square structure at the center. The main component was an integrated heatsink that directly mounts the chip and absorbs the heat generated by the chip and distributes it to the heat sink.

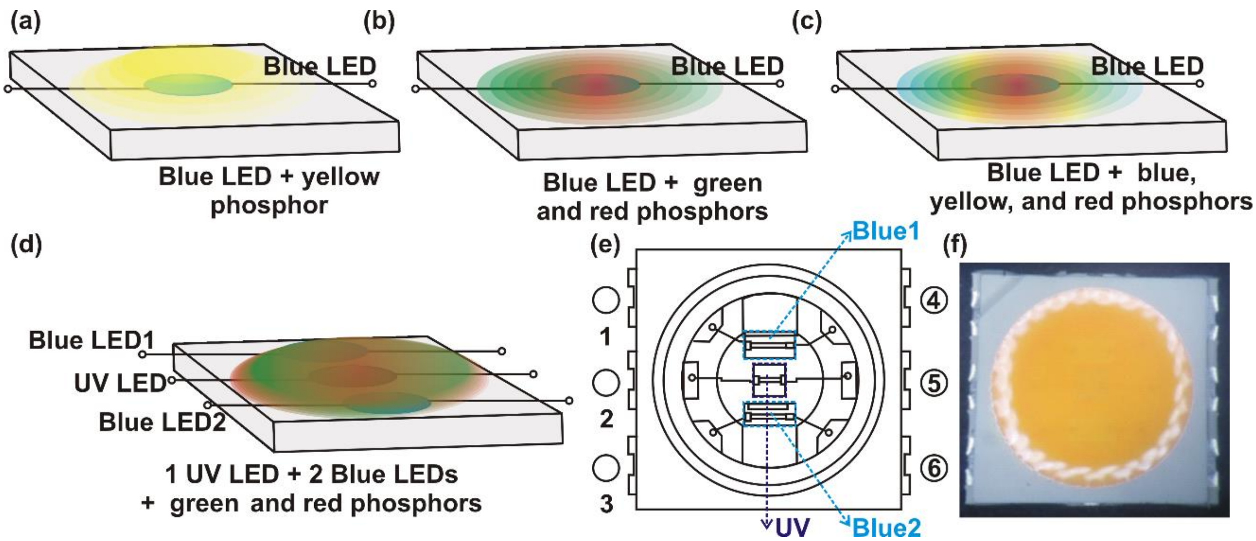

Figure 1 (a-d) Schematic showing the structure of the LED PKGs, (e) sketch of the LED PKG fabricated using two blue LEDs and one UV LED, (f) digital image of the final PKG of the structure shown in (d).

Five LED PKGs were fabricated– (1) blue LED + yellow phosphor (1B-Y), (2) blue LED + green and red phosphors (1B-GR), (3) blue LED + blue, yellow and red phosphors (1B-BYR), (4) and (5) one UV and two blue LEDs + green and red phosphors (PKG-1-1UV2B-GR and PKG-2-1UV2B-GR). Two different PKGs were fabricated using 1UV2B-GR design. In the PKG-1, the wavelength of the blue LED was 452 nm while in PKG-2, the wavelength of the blue LED was 455 nm. The structure of the final PKG of 1UV2BGR configuration was a 3 in 1- type chip in which a UV chip is placed at the center of the PKG and two blue chips were arranged on the top and bottom (Figure 1e). Figure 1f shows the digital image of the final LED PKG.

Figure 2 shows the EL emission spectra and the corresponding CRI points of the conventional Blue LED and phosphor combinations. The 1B-Y PKG has a CRI R_a of 77 and most of the CRI indices exhibit low values which is unsuitable for athletic stadium lighting and UHDTV production (Fig. 2b). Especially R_9 value is negative (-7), indicating that 1B-Y PKG cannot render the red color accurately. This is because of the lack of red component from the 1B-Y PKG. However, we achieved the highest luminous efficacy of 133 lm/W in this 1B-Y LED PKG. In order to enhance the CRI points, firstly we tried two methods. Since the R_9 value (corresponding to the red component) is negative, we fabricated a PKG with blue LED + green and red phosphors (1B-GR) and the corresponding EL spectrum and CRI points are shown in Figs. 2(c-d).

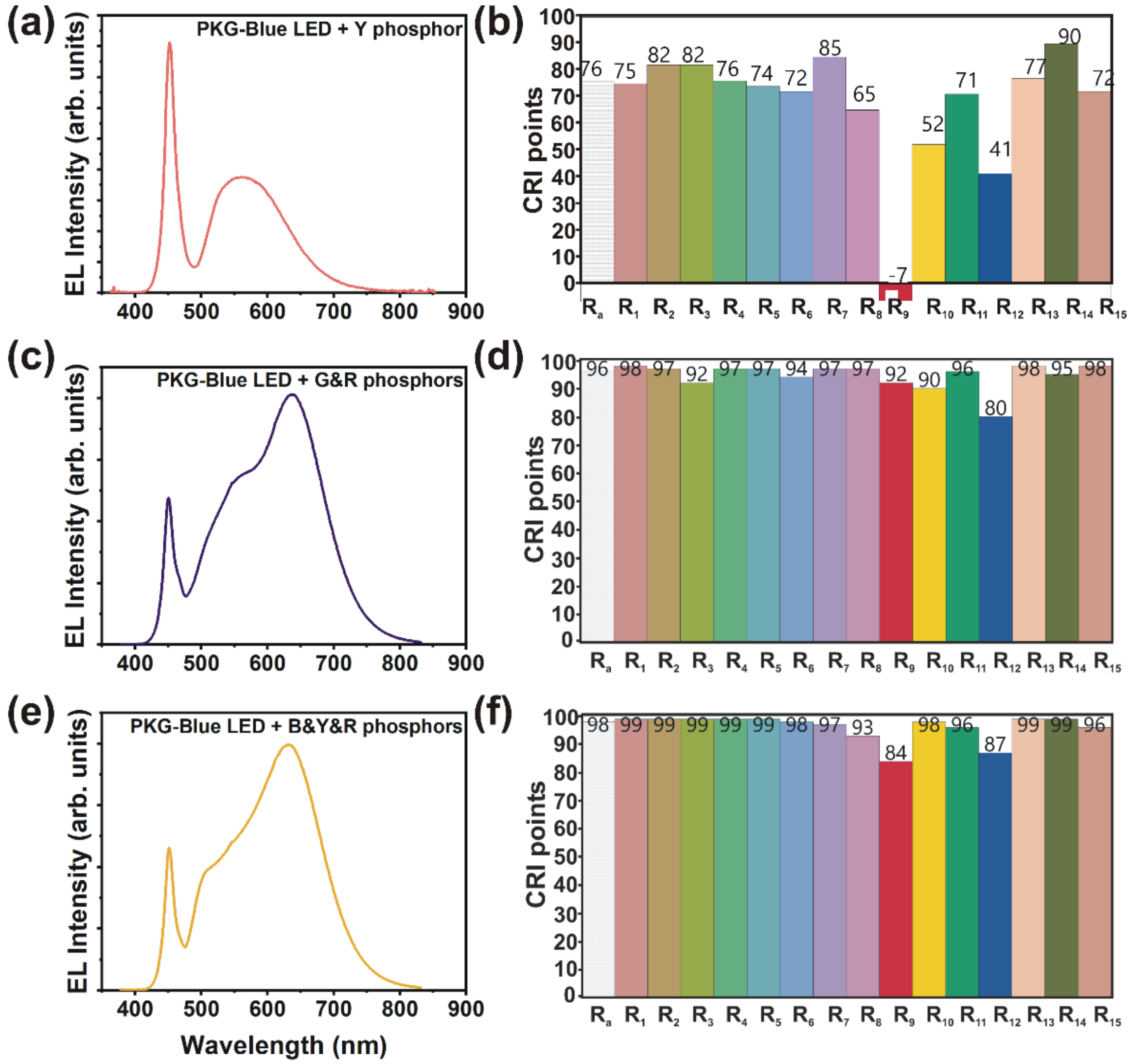

Figure 2 (a, c, and e) EL emission spectra and (b, d, and f) the CRI points of the 1B-Y, 1B-GR, and 1B-BYR LEDs.

Even though we achieved a high CRI R_a of 96.2 in this PKG, the R_3, R_9, and R_{12} values are still below 95. R_{12} corresponds to Munsell code 3PB 3/11 which is an indication of a blue color having an emission peak around 465 nm. In order to compensate for this, we fabricated a PKG comprising of blue LED + blue, yellow and red phosphors. However, it should be noted that the conventional blue phosphor emits light with a peak wavelength of around 490 nm. The EL spectrum and the CRI index points of 1B-BYR LED PKG are shown in Figs. 2(e-f). Again, in this design, we could not achieve all the CRI points above 95. However, it is worth noting that these two LED packages 1B-GR and 1B-BYR, exhibit much better CRI points than 1B-Y PKG.

In these LED PKGs, we tried different combinations of phosphors ratio; however, the CRI points did not exceed 95 with a luminous efficacy above 100 lm/W. It should be noted that CRI points > 95 could be achieved; however, the efficacy will be lower than 100 lm/W because of the trade-off between CRI points and the efficacy of the PKG. We have designed the PKG by keeping the luminous efficacy around 100 lm/W. In order to achieve all the CRI indices above 95 and the luminous efficacy > 100 lm/W simultaneously, we introduced a UV LED chip along with the two blue LEDs in the PKG. We also fabricated one UV and one blue LED chip configuration. However, because of the low efficiency of the UV LED, the overall luminous efficacy of the PKG was well below 100 lm/W. Therefore, we had to use the one UV and two blue LEDs configuration to enhance efficiency. The integration of three LEDs in a chip results in excessive heat generation. Therefore, the heat sink was also designed by taking the heat generation issue into consideration. The strategy to introduce a UV LED resulted in an emission band around 470 nm from the green phosphor.

In order to fabricate LED PKG consisting of 1 UV LED, two blue LEDs along with green and red phosphors, we designed two packages.

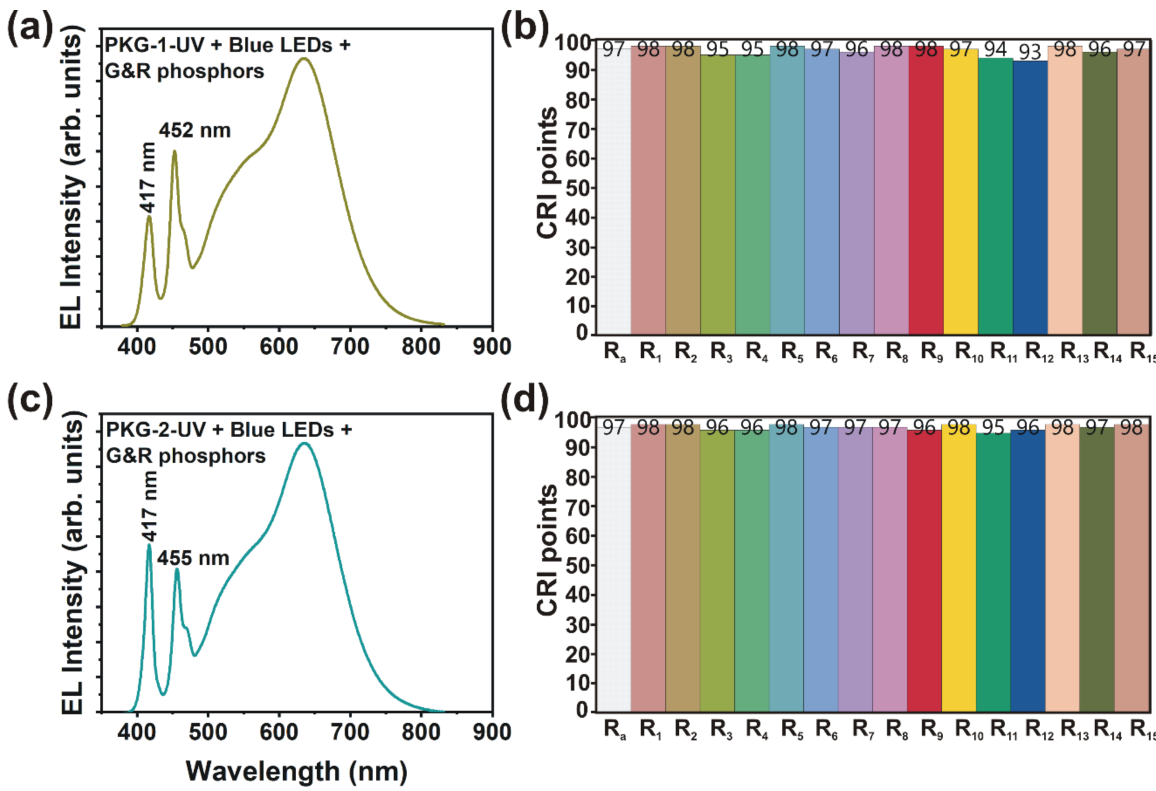

Figure 3 (a and c) EL emission spectra and (b and d) CRI points of the PKG-1-1UV2B-GR and PKG-2-1UV2B-GR LEDs.

In PKG-1, the wavelength of UV LED was 417 nm while that of the blue LED was 452 nm. In the PKG-2, we used the same UV LED with a peak emission wavelength of 417 nm, however, the peak emission wavelength of blue LED was 455 nm. The combination of the 417 nm emission from the UV LED and 455 nm from the blue LEDs were able to satisfy both the high efficiency of PKG and the high color rendering indices (≥ 95). The EL spectra and the corresponding CRI points are shown in Figure 3. In PKG-1, the total current was set to 60 mA (40 mA through two blue chips and 20 mA through UV chip). In PKG -2, 25 mA (15 mA through two blue chips and 10 mA through UV chip) was set. As seen in Fig. 2 (a and c), the emission from UV LED is high in PKG-2. The ratio of the current flowing through UV and blue LEDs was optimized to achieve a luminous efficacy of ≥ 100 lm/W. It should be noted that the R_{11} and R_{12} values were below 95 for the PKG-1-1UV2B-GR LED PKG. This is because the emission wavelength of the blue-chip was around 452 nm. The blue-chip used in the PKG-2-1UV2B-GR LED PKG emits light with a peak wavelength of 455 nm. It is because of the peak emission of 455 nm from this blue chip; we could achieve all the CRI points > 95.

Figure 4 shows the CIE (x,y) coordinates and correlated color temperatures (CCT) of the wLEDs fabricated in this study.

Table1. The CRI R_a, R_9, CIE(x,y) coordinates, CCT values and luminous efficacy of the fabricated LEDs

	CRI (Ra)	CRI (R9)	CIEx	CIEy	CCT (K)	lm/W
1B-Y	76	-7	0.3300	0.3375	5608	133.00
1B-GR	96	92	0.4318	0.4007	3060	106.20
1B-BYR	98	84	0.4365	0.4038	3006	105.71
PKG-1 1UV2B-GR	97	98	0.4234	0.3844	3075	107.31

PKG-2 1UV2B-GR	97	96	0.4363	0.3916	2906	100.12

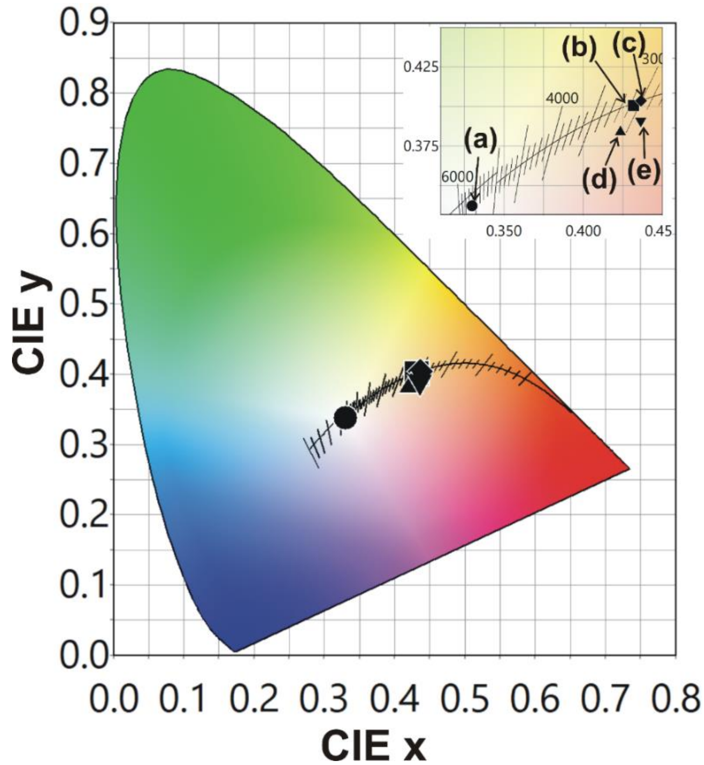

Figure 4 CIE 1931 color coordinates and the corresponding CCT values of (a) 1B-Y, (b) 1B-GR, (c) 1B_BYR, (d) PKG-1-1UV2B-GR and (e) PKG-2-1UV2B-GR

Each coordinate in the CIE 1931 chromaticity diagram represents the CCT value and the coordinates of CIE (x, y) respectively. The CCT and CIE (x, y) coordinates of each PKG are summarized in Table 1. In the inset of Figure 3, an enlarged view is shown. (a), (b) and (c) are the color coordinates and CCT of 1B-Y, 1B-GR, and 1B-BYR LED PKGs and, (d), (e) represents the corresponding coordinates of PKG-1-1UV2B-GR and PKG-2-1UV2B-GR LEDs respectively. When compared to 1B-Y LED PKG, all other LEDs exhibit much warmer emission because of the red component in the 1B-GR, 1B-BYR, PKG-1-1UV2B-

GR, and PKG-2-1UV2B-GR LEDs. Moreover, the CIE coordinates of PKG-1-1UV2B-GR and PKG-2-1UV2B-GR LEDs lie below the black body locus. It is reported that the sources with the CIE coordinates below the blackbody locus have higher preferences.[25–27]

As stated earlier, the CRI R_9 of 1B-Y LED PKG was -7 indicating that the 1B-Y LED PKG has poor or no red color rendering ability. As the CRI points are scaled between 0 and 100, a negative CRI point does not provide any information. If two WLEDs have different negative CRI point, then it is impossible to compare the particular color rendering ability. CRI Ri is calculated using the following equation[16,24]

$$R_i = 100 - 4.6\,\Delta E_i \qquad (1)$$

where ΔE is the shift in the color/color differences. If $\Delta E \geq 22$ then R_i will show negative values.

In order to evaluate the fabricated LEDs in this study properly, the LEDs were further evaluated using the TM-30 standard method. In the TM-30 standard 99 color samples are used to evaluate the light source's performance. Except for 1B-Y LED, all other LED PKGs exhibit high color fidelity in TM-30 standard. Figures 5 (a,c, and e) show color vector graphics (CVGs) and Figs. 5 (b, d, and f) show the local chroma shifts of the light emitted from the 1B-Y, 1B-GR, and 1B-BYR LEDs (red circles) compared to the reference illuminant (black circles). The arrows in Figs. 5 (a,c, and e) indicate the shift of the 16 hue bins compared to those of the reference illuminant.

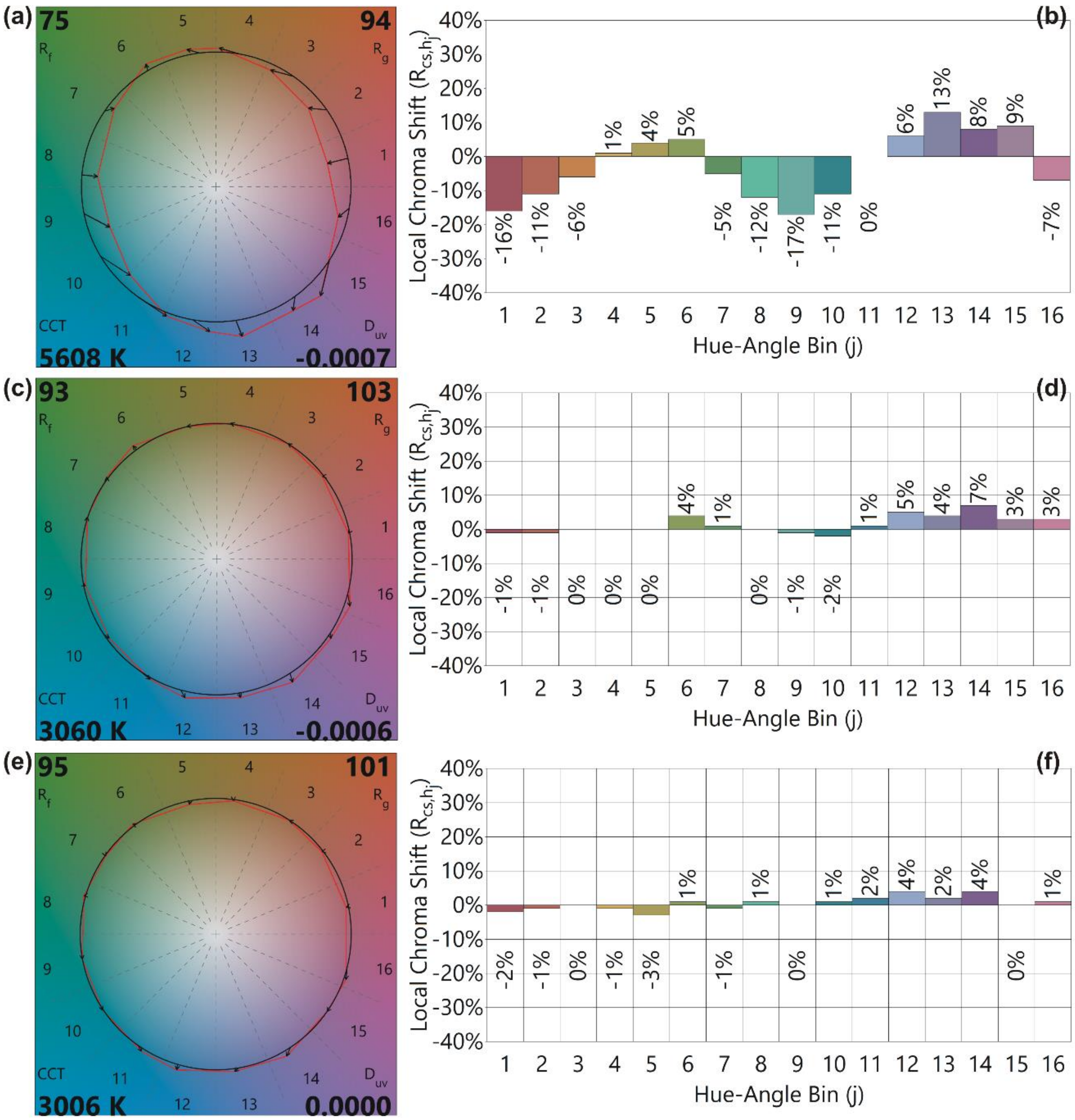

Figure 5. (a, c, and e) TM-30-18 color vector graphics (CVGs) and (b, d, and f) local chroma shifts of the 1B-Y, 1B-GR, and 1B-BYR LEDs. The reference illuminant is shown by a black circle and the red circles represent the CVGs of the fabricated LEDs. The arrow indicates the corresponding color change induced by 16 hue bins compared to the reference illuminant.

As evident from the CVGs, the 1B-Y LED PKG exhibit a decrease in the all the 16 hue bins whereas the 1B-GR and 1B-BYR LED PKGs to exhibit much lesser shifts from those of the reference illuminant. The Chroma shifts indicate the relative percentage (positive/negative) shifts of the 16 hue-angle bins. The CVG of 1B-Y LED show that the light source fabricated using 1B-Y LED will result in less saturated images. As expected the 1B-Y LED PKG exhibit a large shift of the local Chroma values. For 1B-Y LED PKG, most of the Chroma values show a negative shift and the shift up to -17% is observed. On the other hand, the CVGs of 1B-GR and 1B-BYR exhibit lesser shift of the 16 hue bins. The red circles (our LED) almost overlap with the black one (reference illuminant). The local Chroma shifts for the 1B-GR and 1B-BYR were under 7% and 5%, respectively. The D_{uv} – a measure of the CCT value shift from the black body locus is -0.007 for 1B-Y LED PKG. The D_{uv} of the 1B-GR is -0.0006 and 0 for 1B-BYR. Note that the CCT value of the 1B-BYR LED PKG is 3006 which lies almost on the black body locus and therefore no shift from the black body locus is observed.

The CVGs and the local Chroma shift of the PKG-1-1UV2B-GR and PKG-2-1UV2B-GR LEDs are shown in Figure 6. The local Chroma shifts for these LEDs are under 7%; mostly positive shifts. The D_{uv} values are -0.0061 and -0.0050 for PKG-1-1UV2B-GR and PKG-2-1UV2B-GR LEDs respectively, indicating that these light sources will be highly preferred.

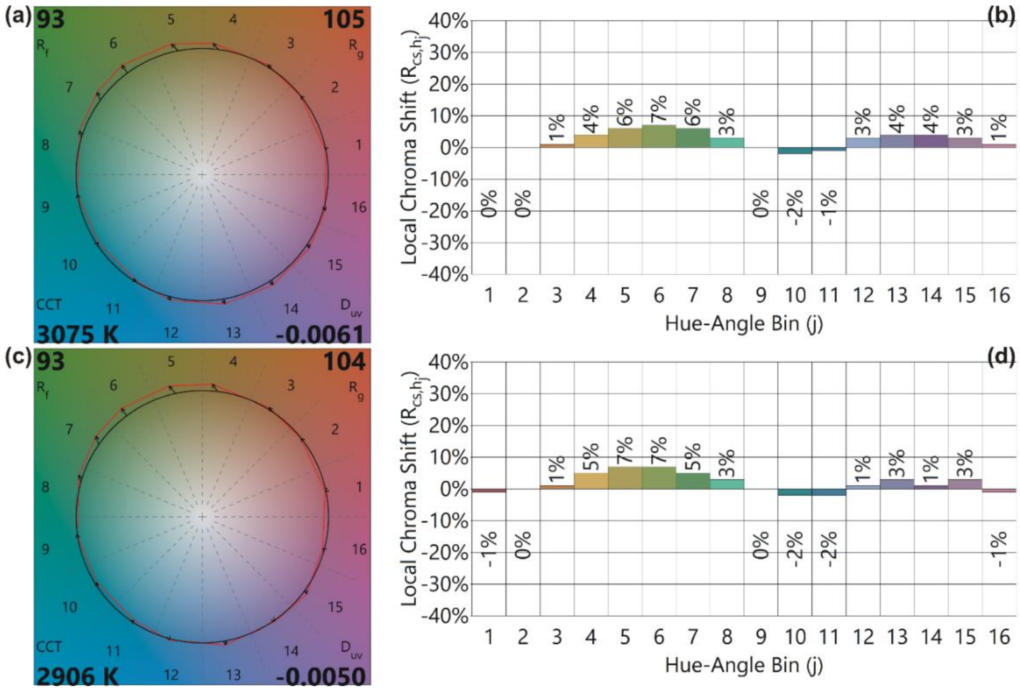

Figure 6. (a and c) TM-30-18 color vector graphics (CVGs) and (b and d) local chroma shifts of PKG-1-1UV2B-GR and PKG-2-1UV2B-GR LEDs. The reference illuminant is shown by a black circle and the red circles represent the CVGs of the fabricated LEDs. The arrow indicates the corresponding color change induced by 16 hue bins compared to the reference illuminant.

Figure 7a shows the R_g vs R_f plot of the fabricated LEDs. The ideal value of the (R_g, R_f) is (100, 100). The deviation of the values indicates whether the light source produces under/over saturated images or low fidelity images. The 1B-Y LED PKG exhibits low R_g and R_f values indicating the LED produce low fidelity and low-saturated images. All the other LED PKGs exhibit reasonable (R_g, R_f) values. The optimum value was achieved for the 1B-BYR LED PKG which has (R_g, R_f) values of (95, 101) and produces images with high fidelity and nearly perfect saturation. Note that 1B-BYR LED PKG did not have all the CRI points above 95. The PKG-1-1UV2B-GR and PKG-2-1UV2B-GR LEDs can be used to produce images with high fidelity and high saturation because of its high (R_g, R_f) values.

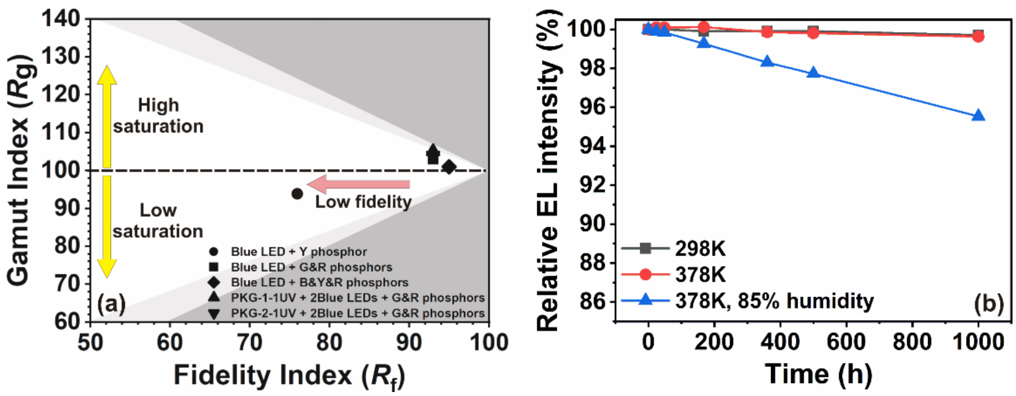

Figure 7 IES TM-30-18 Fidelity index (R_f) and gamut index (R_g) of the fabricated LEDs. Light grey region – Approximate limits for sources on the Planckian locus, Dark grey region – Approximate limits for practical light sources.

It is worth noting that the R_f value is lower than the CRI (Ra) value in all the LED PKGs. This is because the TM-30 standard uses 99 color samples whereas CIE R_a uses only 8 sample colors. Therefore, R_f can be lower than R_a. Finally, the long term stability and reliability of the newly designed PKG-2-1UV2B-GR LED was tested under various test environments. The reliability data is shown in Figure 7b. The LEDs were tested by keeping it ON at 298 K, 378 K, and 378 K, 85% humidity for 1000 h. The emission intensity was 99.7% of the initial value even after 1000 h of operation. In addition, the sample was placed under 378K and a current of 180 mA was applied to measure the change of the luminous flux up to 1000 h and the luminous emission intensity of 99.6% of the initial emission intensity was maintained even after 1000 h of continuous operation.

Finally, the PKG-2-1UV2B-GR LED was kept in a chamber having a temperature of 378K and a humidity of 85%, and the durability under stress conditions was confirmed. The PKG-2-1UV2B-GR LED exhibited a high luminous intensity of 95.5% of the initial emission intensity suggesting that the fabricated LEDs are highly reliable and durable even under stress conditions. The newly designed LED PKGs having a high efficacy of 100 lm/W, high CRI points above 95, and high durability will find applications in artificial stadium lighting, UHDTV production, and applications where highly efficient and high color rendering WLEDs are required.

4. Conclusion

In order to utilize the wLEDs for most of the application that requires sunlight-like quality, LED PKG with CRI (R_1-R_{15}) points exceeding 95 were fabricated using a re-designed LED PKG consisting of one UV LED, 2 blue LEDs and green & red phosphors. The fabricated LED PKGs not only exhibit CRI R_1-R_{15} points above 95 but also have a luminous efficacy above 100 lm/W. We achieved high efficiency and CRI points above 95 through adjusting the peak emission wavelength of UV and blue LEDs, current ratio through the LEDs and the green/red phosphor mixing ratios. An optimized CRI Ra of 97.3 with the efficiency of 100.12 lm/W and CCT of 2906K was achieved from the PKG-2-1UV2B-GR LED. A high CRI R_a of 98 was achieved in 1B-BYR LED package. The fabricated LEDs were evaluated using TM-30-18 color vector graphics, local Chroma shifts, and fidelity-gamut plot. The newly designed LED PKGs exhibit high fidelity and high saturation. The LEDs also exhibit high stability and reliability exhibiting a stable operation up to 1000 h under 378 K, 85% humidity test conditions. Our study on the re-designed LED PKG consisting of one UV LED, two blue LEDs + green and red phosphors paves the way to fabricate and use WLEDs in stadium lighting and UHDTV production where high CRI points are required.

3. Experiment

3.1 LED PKG design

In this study, eight middle size chips of each LED chip manufacturer were selected and compared with each other. The test LEDs were fabricated in this study using various LEDs developed by various companies. Considering the luminous efficacy and CRI points, we have used 2140 LED chips in this study. In order to realize high CRI and improve the light efficiency of the PKG, six power terminals (two for each LED) were used to individually control the currents of the bonded chips. Also, the PKG includes an integral heatsink for absorbing heat generated from the chip and dispersing the heat into a heat radiator and a terminal for applying an external power source. The PKG designed in this study is characterized by the structure of a single encapsulation for phosphor that can bond blue and UV chips simultaneously and phosphors that can absorb the excitation light of two wavelengths (UV and blue).

3.2 Selection for silicone encapsulant

In the LED PKG, the role of an encapsulant is to protect the chip and the bonding wire inside the PKG from physical impact or external environment. Additionally, it serves as a medium to emit light generated from the UV/blue chip as well as the phosphor. Silicone encapsulant for protecting chips and wire has a double reflector structure for stable filling and a high heat resistant resin was used for achieving high reliability. In this newly designed PKG structure, a silicone resin was newly made by mixing pure silicone and phenyl-based silicone, and the content and mixing ratio of green and red phosphors were optimized to produce PKG having all the CRI points equal to or above 95. The basic characteristics that the encapsulant used for the LED PKG should have are physically resistant to the high heat generated at the UV/blue LED junction, and the interfacial adhesion must be ensured to protect LED from the external high temperature and high humidity environment. To ensure the reliability of the PKG and to maximize the efficiency of light extraction, phenyl-based silicone was used as an encapsulant.

3.3 Materials

The yellow phosphor used in this study is commercial YAG:Ce^{3+} phosphor. The green and red phosphors are GNYAG3757 and R6634 developed by Intematix. Two blue LED chips were used in the study with the peak emission wavelengths around 452 and 455 nm.

3.4 Characterization of the fabricated LEDs

To evaluate the efficiency of the chip, EL spectra were recorded using CAS 140CT (Instrument Systems, Germany) and 500 mm integrating sphere. The forward current to the LEDs was applied using the constant current source K2425 (Keithley). The output characteristics of the fabricated LEDs were evaluated using the CIE and TM-30-18 standards.

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Author contributions

YNA and KDK conducted the experiment. YNA and GA analyzed the results and co-wrote the manuscript. KDK and GSK measured the EL characteristics. The whole work was carried out under the guidance of JSY.

Competing Interests

The author(s) declare no competing interests.

Data availability statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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