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The Comparison of the Application of Two Different Color Quality Evaluation Methods

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Abstract – In this paper, the fabrication of a white light-emitting diode (WLED) package capable of producing different color rendering indexes (CRI (R_a)) using different types of phosphors (YAG:Ce, Silicate, Nitride, LuAG) for the LEDs is presented. The color quality is evaluated based on the current and temperature variation conditions. The evaluation method for color quality compares the existing CIE 13.3 method and the new IES TM-30-15 method. The CRI (R_a) defined in the conventional CIE 13.3 has the disadvantage. This cannot offer any information relevant to the user's preference. However, the newly proposed IES TM-30-15 method suggests the additional measure related to user's preference such as Color Gamut (R_g). The present experimental results obtained using the IES TM-30-15 show that the color quality of the WLEDs using green and red phosphors are better than that of the WLEDs using yellow phosphor, but their luminous efficacies are lower. The color quality of WLEDs using green and red phosphors are more stable than that of the WLEDs using yellow phosphor, for current and temperature variations, and it is verified that the phosphor causes this change. The evaluation method for color quality, based on IES TM-30-15, is proved to be capable of overcoming the problems of the existing evaluation methods by this study.

Keywords: Color fidelity, Color gamut, Color quality, Color rendering index (CRI), Phosphor-converted white LED (PC-WLED).

1. Introduction

Light-emitting diodes (LEDs) are widely replacing traditional light sources in day-to-day applications because of their advantages such as high luminous efficiency, long life, high reliability, and energy saving [1, 2]. Phosphor-converted white LEDs (PC-WLEDs) are generally made from blue-LED chips coated with yellow phosphor $Y_3Al_5O_{12}$: Ce^{3+}(YAG : Ce). However, the WLEDs made using yellow phosphor lack the red wavelength component, and hence, have limitations in achieving high color rendering (approximately 80). Thus, much attention has been paid to the development of green and red phosphors for LEDs to improve color rendering [3, 4]. Currently, the following phosphors for LEDs have been commercialized: silicate phosphor ($Sr_2SiO_4 : Eu^{2+}$, $Ba_2SiO_4 : Eu^{2+}$), aluminate phosphor (YAG:Ce, LuAG:Ce), oxynitride phosphor ($BaSi_2O_2N_2 : Eu^{2+}$, β-SiAlON:Eu^{2+}), and nitride inorganic phosphor ($La_3Si_6N_{11} : Ce^{3+}$, $Sr_2Si_5N_8:Eu^{2+}$, (Ca,Sr)$AlSiN_3 : Eu^{2+}$) [5, 6]. YAG : Ce or silicate-based yellow phosphor shows relatively higher luminous efficacy (luminous flux/power, lm/W), but there is a limit to realize high color rendering property. When a silicate-based green phosphor and a nitride-based red phosphor are used together, a high color rendering index and a wide excitation wavelength can be obtained. However, when green and red phosphors are used together, the luminous efficacy and the movements of the color coordinates are reduced, as red phosphor with large excitation wavelengths reabsorbs the green light emitted from the green phosphor. Another reported problem of the PC-WLED is that its characteristic changes according to the operating conditions and temperature environment [7-9].

Several studies have been conducted on the methods for the evaluation of color quality and on the development of light sources capable of high color rendering. The color rendering index (CRI) is the only internationally recognized standard measure for color quality. A color rendering index (CRI) is a quantitative measure of the ability of a light source to reveal the colors of various objects faithfully in comparison with an ideal or natural light source. However, the CRI was developed to evaluate the band spectrum of the gas discharge lamp, and a number of issues were reported with the development of white-light sources with continuous spectra, such as LEDs [10, 11]. The CRI (R_a) defined by the International Commission on Illumination (CIE) employs eight test color samples (R1–R8) with low chroma, and produces a single arithmetic average value using the difference between the chromaticity measured under the test light source and the chromaticity calculated when a reference illuminant is used. Thus, light sources whose spectra are different can have the same Ra value even if their R1–R8 values are different. In addition, a special CRI that corresponds to R9-R15 cannot be

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determined using the Ra value alone. Therefore, although LEDs may be able to represent the saturated chromaticity of objects, their CRIs may be evaluated as low. To overcome this shortcoming, a number of researchers started working on a new evaluation method. As a result, in 2015, the IES TM-30-15 was published by the Illuminating Engineering Society of North America (IESNA) [12], as a new evaluation method. This method solved the problem of the CRI; that the color quality was represented using a single number. Instead, it represented the color quality using the color fidelity (R_f), color gamut (R_g), and color vector graphic.

In our study, a WLED with improved CRI was fabricated using the existing commercial phosphors for LEDs (yellow, red, and green colors) and its characteristics were evaluated. Firstly, color quality was evaluated according to phosphor type and composition ratio. Secondly, color quality change according to current and temperature was also evaluated. The samples were actually fabricated according to the phosphor type and composition ratio of the white LED and the two color evaluation methods were compared to verify that the new evaluation method (IES TM-30-15) complemented the problems of the existing evaluation method (CIE 13.3).

2. Evaluation Methods

Two evaluations were conducted through experiments. First, the color quality was evaluated for different types of phosphor and different composition ratios. Next, the color quality was evaluated for current and temperature variations.

2.1 Sample fabrication and experimental methods

The LED package employed a single blue-LED chip based on InGaN whose peak wavelength was 450 nm, as shown in Fig. 1. Its size was 5.4 mm × 5.0 mm, and it was fabricated with a surface-mounted device (SMD) of 0.2 W.

Twenty-five samples (five types of packages, each with five samples) were fabricated, for different phosphor types and different composition ratios, on a single blue chip. As presented in Table 1, five types of packages were fabricated as follows: ① package mounted with only blue chip, ② package encapsulated with silicone only in the blue chip, ③ package using YAG:Ce yellow phosphor in the blue chip, ④ package using silicate green phosphor and nitride red phosphor in the blue chip, and ⑤ package using LuAG green phosphor and nitride red phosphor in the blue chip. Fig. 2 shows a printed circuit board (PCB) mounted with resistance temperature detectors (RTDs) and LED packages.

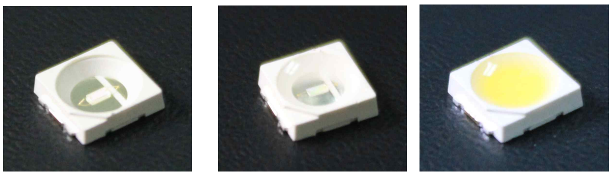

(a) (b) (c)

Fig. 1. Fabricated LED package: (a) mounted blue chip, (b) encapsulated with silicone, and (c) encapsulated with phosphor and silicone

Table 1. Classification based on different phosphor types and composition ratios.

Sample	Emission	Ratio (%)		Total molding compound (mg)
		Silicone	Phosphor	
①	Bare	0	N/A	0
②	Clear	100.0	N/A	7.3
③	Yellow	92.0	YAG 8.0	7.3
④	Green+ Red	90.0	LuAG 9.5 +Nitride 0.5	7.3
⑤	Green+ Red	88.7	Silicate 9.4 +Nitride 1.9	7.3

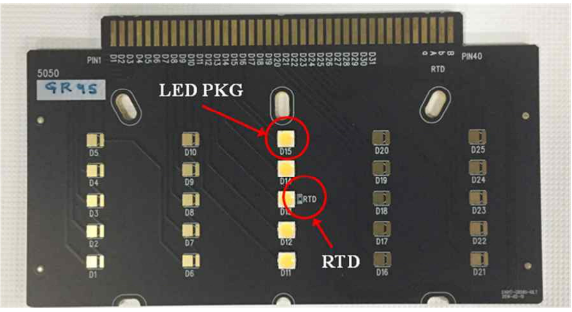
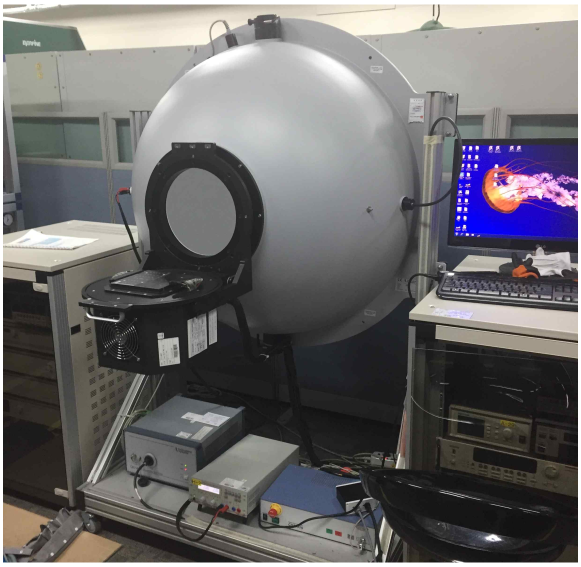


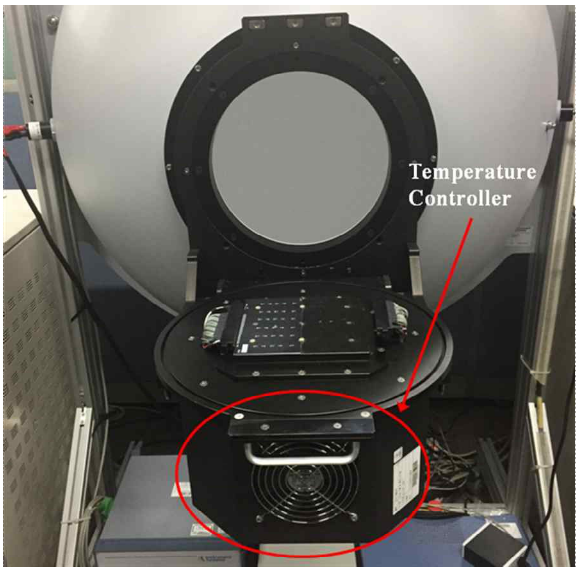
Fig. 2. PCB mounted with RTD and LED packages

The experimental method is as follows : Two factors temperature and supplied current were controlled as shown in Fig. 3 to measure the spectrum power distribution (SPD) in the WLED. The operating conditions of the chip are 120 mA for the maximum current and 85 degrees for the maximum temperature. If the current greater than 90mA is applied at the constant temperature of 25 degrees, the following changes are expected to occur. The CCT value increases for YAG 21 while relatively smaller changes can be observed for GR 84 and GR 95. The CRI value, however, will not be varied. For evaluating the effects of temperature variations, a PCB mounted with an LED was installed in a heat sink mounted with a cooling fan, and the temperature was increased from 25 °C to 85 °C in steps of 5 °C, using an RTD, during LED lighting. For current control, a DC power source (Keithley, Tektronix, Inc.,) was used to increase the current from 30 mA to 90 mA in steps of 10 mA. For SPD measurements, an integrating sphere (1.0 m) and spectrometer (CAS 140 CT, Instrument Systems GmbH) were used to measure the SPDs of all five samples of each of the five types of LED packages presented in Table 1.

First, the color quality was evaluated using the mean



(a)



(b)

Fig. 3. Measurement equipment: (a) integrating sphere (1.0 m), (b) temperature controller

value of the SPD when the temperature of the PCB was 25 °C and the supplied current was 60 mA. Next, the color quality was evaluated using the mean value of the SPD when the PCB temperature was increased from 25 °C to 85 °C in increments of 5 °C and the supplied current was increased from 30 mA to 90 mA in increments of 10 mA. The evaluation method for color quality compared the results of the existing CIE 13.3 method and the new IES TM-30-15 method.

2.2 Color quality evaluation methods

The difference between the CRIs used in CIE 13.3 and the new evaluation method IES TM-30-15 is investigated first. The CRI used in CIE 13.3 employs a test color method. For test color samples in the test color method, eight samples (R1 to R8) are used, and a single arithmetic mean value R_a is obtained using the difference between the chromaticity calculated while illuminating a reference illuminant and the chromaticity measured under a test source. The reference illuminant used is a Planckian radiator when the correlated color temperature (CCT) is less than 5000 K, and a CIE daylight illuminant when the CCT is greater than 5000 K. Fourteen test color samples, including the R9 to R15 specified in the CIE, are set and the color appearance based on the reference illuminant (6500 K, D65) and the color differences under the test light source are quantified. The CRI is calculated from the color difference (ΔE_i) of the CIE 1964 (W*U*V*) uniform color space, which is calculated based on the Von Kries chromatic adaptation transform (CAT), as shown in (1). Here, the CRI (R_a) is a mean value of R_i where i varies from one to eight, as shown in (2).

$$R_i = 100 - 4.6\Delta E_i \tag{1}$$

$$R_a = \frac{1}{8}\sum_{i=1}^{8} R_i \tag{2}$$

The new evaluation method IES TM-30-15 is different from the existing method the differences are summarized in Table 2 and are detailed below. First, the color adaption transform model of CIE CAM02, which was revised in 2002, is additionally applied to the CIE 1964 U*V*W* calculated based on the Von Kries CAT, in the TM-30 method. Second, the existing CRI method employs 14 test color samples (TCSs) whereas the new TM-30 method uses 99 color evaluation samples (CES). The 99 CESs are extracted from the existing 105000 object colors to represent visually distinguishable colors. Third, in the existing CRI evaluation, a Planckian radiator is applied for CCTs below 5000 K and the CIE daylight illuminant is used for CCTs above 5000 K. This results in a discontinuous characteristic because of the difference in the reference illuminant. The TM-30 method overcomes this problem by applying a continuous reference illuminant

Table 2. Comparison of color quality evaluation methods

CRI Calculation Engine (1974)	TM-30 Calculation Engine (2015)
CIE 1964 U*V*W*	CAM02-UCS (CIECAM02)
8 color samples (+6 color samples)	99 color samples
Ref Illuminant Step Function If <5000 K, Planckian radiator If ≥5000 K, CIE Daylight series illuminant	Ref Illuminant Continuous Uses same reference sources, but blended between 4500 K and 5500 K
Fidelity Metric Only (R_a)	Fidelity (R_f), Gamut (R_g), Graphical (Color distortion and saturation), Detailed (hue angle, increase or decrease in chroma)
No lower limit for scores	0 to 100 scale (fidelity)

between 4500 K and 5500 K. Fourth, the CRI method is shortcoming in evaluating the color quality for light sources that have the same CRIs but different spectra, as it uses only the CRI, which represents the color quality using a single number. This is because users mostly prefer light sources that reveal an object more clearly. Thus, an additional index is needed to distinguish a light source according to its vividness and represent an increase or decrease in the chroma. To overcome this problem, certain indexes are added in the TM-30 method, to represent a color difference, such as the color fidelity (R_f), color gamut (R_g), or color vector graphic. Finally, the CRI may have a negative value, which can confuse users. This is overcome in the TM-30 method by using a scale of fidelity between 0 and 100.

Color fidelity (R_f) refers to an index that represents the closeness to a reference illuminant, and is the same concept as the existing CRI concept. The reference illuminant shall be Planckian radiation, a CIE Daylight Series illuminant. More specifically, the R_f is calculated by determining the difference between the chromaticity coordinates under the test illuminant and reference illuminant, then determining the arithmetic mean of the color difference. It evaluates the similarity of an object color reproduced under a test light source with the color reproduced under a reference illuminant. R_f is calculated according to (3) and (4) via the CIE CAM02-UCS color difference (ΔE_{Jab}), which can be represented by a value between 0 and 100. Color gamut (R_g) refers to an index that represents an increase or decrease in the chroma. The chroma is the the quality of a color's purity, intensity or saturation. It evaluates the area of increase or decrease in the chroma of the object color under a sample light source, with respect to the value obtained using a reference illuminant. It can be calculated using (5), where A_r refers to the area of a polygon of the reference illuminant constructed with 99 CESs in the color coordinate domain (a'b') of the CIE CAM02-UCS and A_t refers to the area of the polygon of the test light source. The color vector graphic (see Fig. 6) shows the graph of the decrease or increase in the hue and chroma under the test light source, compared with those of a reference illuminant (white circle in Fig. 6). An R_g value of 100 indicates that, on average, the test source does not increase or decrease chroma compared to the reference illuminant. An R_g value greater than 100 indicates an overall increase in chroma, whereas an R_g value less than 100 indicates an overall decrease in chroma.

$$. R'_f = 100 - 7.54 \frac{1}{99} \sum_{i=1}^{99} (\Delta E_{Jab,i}) . \tag{3}$$

$$R_f = 10 \ln(e^{R'_f/10} + 1) \tag{4}$$

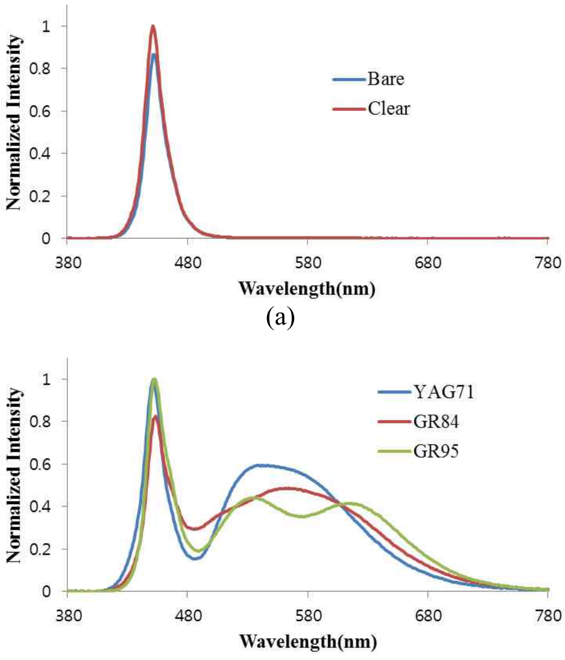
$$R_g = 100 \times \frac{A_t}{A_r} \tag{5}$$

3. Results and Discussion

3.1 Color quality evaluation according to phosphor types and composition ratios

Fig. 4 shows the SPDs for different phosphor types and composition ratios when the temperature of the PCB is 25 °C and the supplied current is 60 mA. Among the packages presented in Table 1 above, the package mounted with only the blue chip (①) is called "bare"; the package encapsulated with silicone only in the blue chip (②) is called "clear"; the package using YAG:Ce yellow phosphor in the blue chip (③) is called "YAG 71"; the package using the silicate green phosphor and nitride red phosphor in the blue chip (④) is called "GR 84"; and the package using the LuAG green phosphor and nitride red phosphor in the blue chip (⑤) is called "GR 95". The bare and clear packages in Fig. 4 (a) emit light at the peak wavelength of 451 nm. The YAG 71 package in Fig. 4(b) emits light at the peak wavelength of 451 nm on account of the InGaN blue chip, and at the peak wavelength of 547 nm on account of the yellow phosphor. GR 84 emits light at 453 nm (due to the blue chip) and at the peak wavelength of 547 nm (due to the green and red phosphors). GR 95 emits light at 452 nm (due to the blue chip) and at the peak wavelengths of 535 nm (due to green phosphor) and 615 nm (due to red phosphor).

Table 3 presents the CRI (R_a), R_f, R_g, CCT, and luminous efficacy of each package. In YAG 71, the R_a is 71, R_f is 72, R_g is 90, CCT is 5806 K, and luminous efficacy is 160 lm/W, which is the highest. In GR 84, the R_a is 84, R_f is 82,



(a)

(b)

Fig. 4. Photometric spectrum of LEDs: (a) bare and clear packages, (b) YAG 71, GR 84, and GR 95 packages

Table 3. Color quality evaluation results

Sample	Package	CRI (R_a)	R_f	R_g	CCT [K]	Luminous efficacy [lm/W]
①	Bare	N/A	N/A	N/A	N/A	18
②	Clear	N/A	N/A	N/A	N/A	21
③	YAG 71	71	72	90	5806	160
④	GR 84	84	82	92	5509	141
⑤	GR 95	95	87	102	5738	126

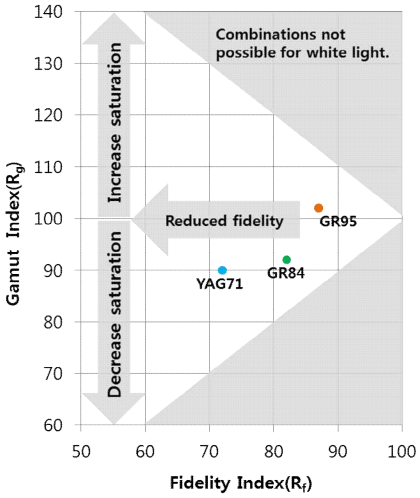
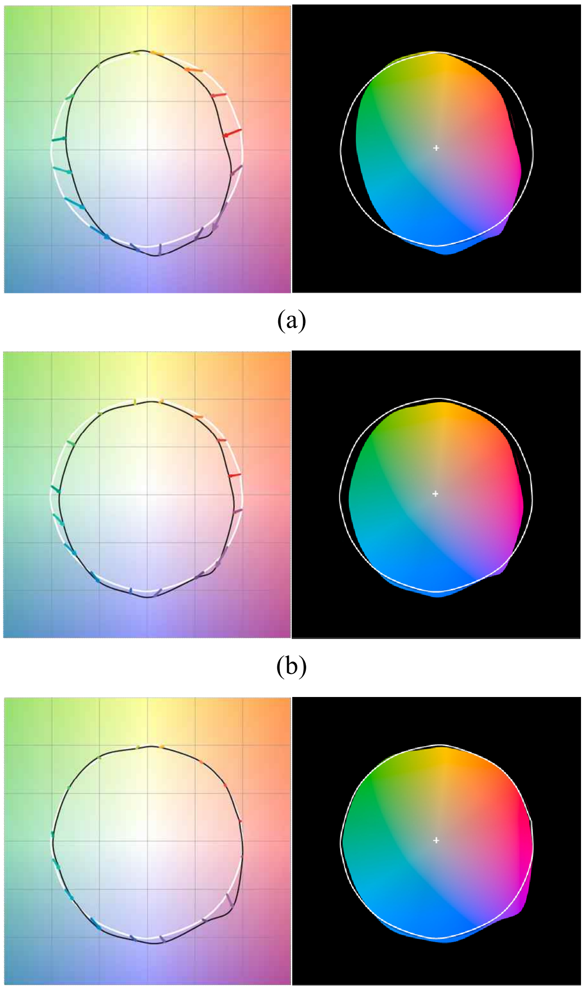


Fig. 5. Fidelity index (R_f) and Gamut index (R_g)

R_g is 92, CCT is 5509 K, and the luminous efficacy is 141 lm/W. In GR 95, the R_a is 95, R_f is 87, R_g is 102, CCT is 5738 K, and the luminous efficacy is 126 lm/W. The above result verifies that the CRIs of the packages using the green and red phosphors are higher than 80, which proves the improvement in the CRI; however, the luminous efficacy is lower.

Figs. 5 and 6 show the R_f, R_g, color vector graphic, and color distortion graphic for the IES TM-30-15 evaluation method. The horizontal axis in Fig. 5 represents R_f and the vertical axis represents R_g. The white area inside the triangle refers to the boundary of the existing light source [13]. In YAG 71 using a yellow phosphor, the R_f is larger than the R_a, but in GR 84 and GR 95 using green and red phosphors, respectively, the R_f is evaluated as being lower than R_a. This is because the number of CESs used in the R_f evaluation, 99, is larger than the number of TCSs used in the existing R_a evaluation, 8. Thus, a light source whose existing R_a is higher may have lower R_f. If R_g>100, the chroma of the object color is expected to increase, and if R_g<100, the chroma of the object color is expected to decrease. Thus, since the R_g in GR 95 is increased to 102, GR 95 can observe a color more vividly than YAG 71 or GR 84.


(a)

(b)

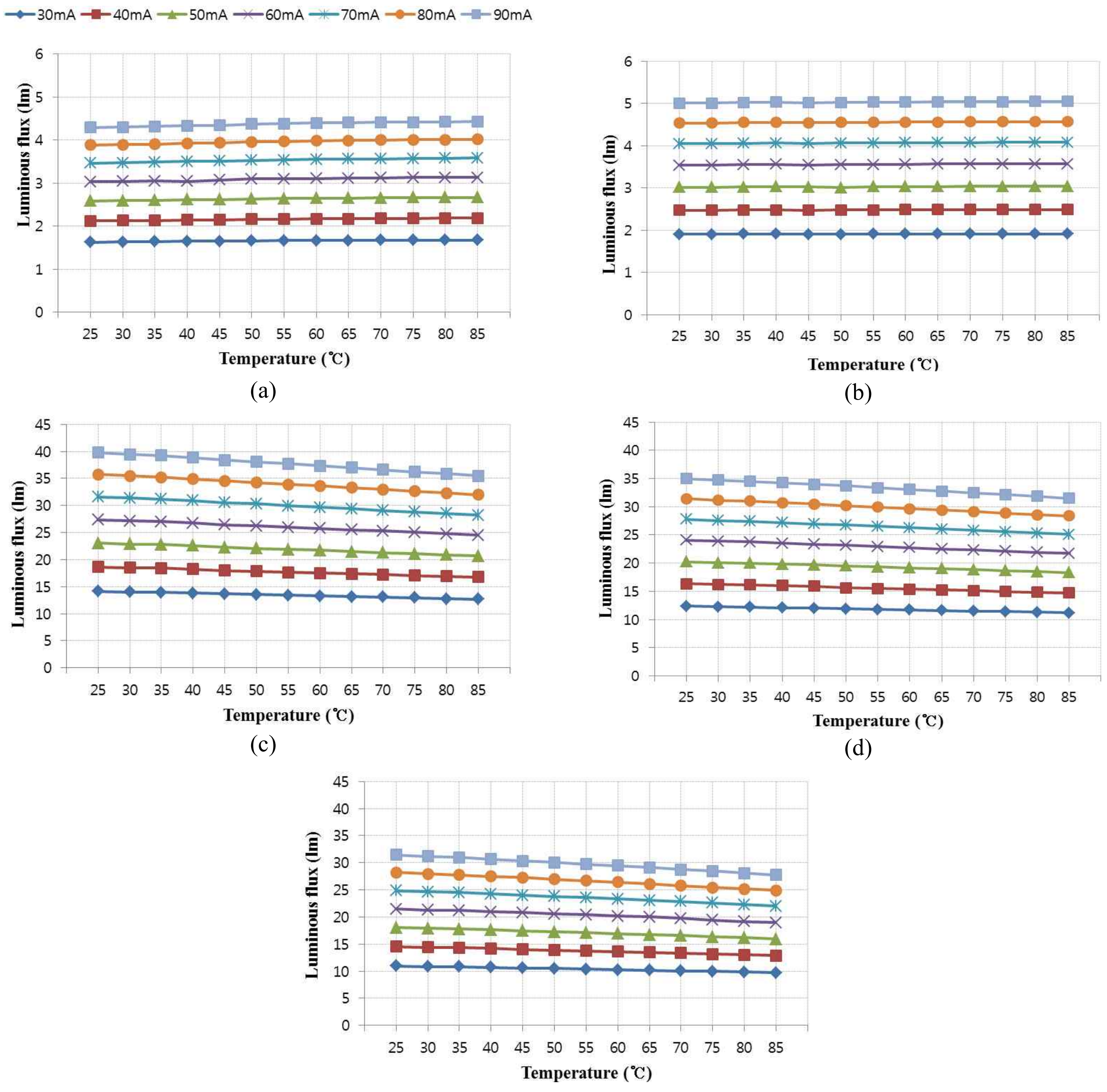
(c)

Fig. 6. Color vector graphic and color distortion graphic: (a) YAG 71 package, (b) GR 84 package, (c) GR 95 package

Fig. 6 shows the graph of a polygon in which the mean values of color coordinates located in each bin are connected after configuring 16 hue bins by dividing the color coordinate (a'b') domain of CIECAM02-UCS by 22.5°. It can identify the color whose chroma is decreased or increased in the sample light source, compared to the reference illuminant, and the amount of hue shift that occurs. Since the red and green regions in YAG 71 using yellow phosphor were reduced, and GR 84 employed green and red phosphors, its red and green regions were increased more than that of YAG 71. Since all regions of GR 95 are almost consistent with those under a reference illuminant, GR 95 is regarded as a light source with excellent color quality.

3.2 Color quality evaluation according to current and temperature variations

The luminous flux and color quality were evaluated by increasing the PCB temperature from 25°C to 85°C in increments of 5°C; the supplied current was increased from 30 mA to 90 mA in increments of 10 mA. Fig. 7 shows the changes in luminous flux for the five package types when



(a)

(b)

(c)

(d)

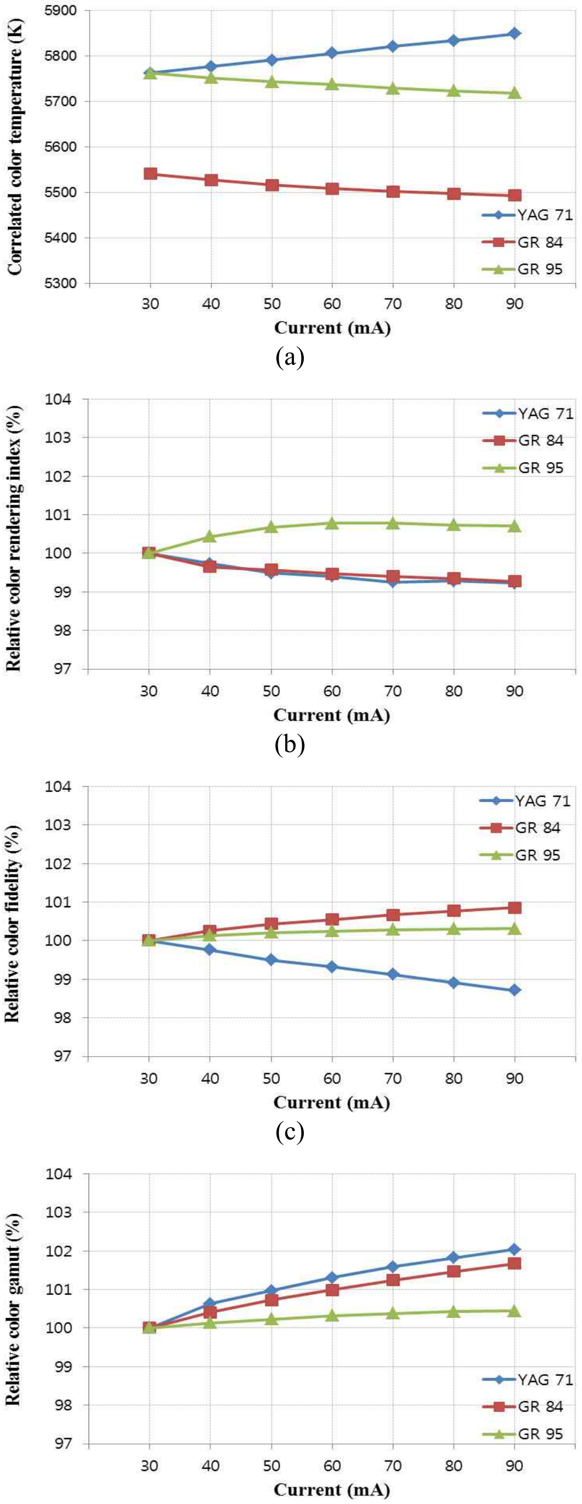
(e)

Fig. 7. Luminous flux of white LED with temperature and current variations: (a) bare package, (b) clear package, (c) YAG 71 package, (d) GR 84 package, and (e) GR 95 package

the temperature and current are increased. As the current is increased, the luminous fluxes of all types of packages are also increased constantly. The bare and clear packages were analyzed to determine the effect of the silicone encapsulant on the changes in the luminous flux, according to the temperature of the package. The measurement results showed that the changes in luminous flux were minimal for the bare and clear packages even when the temperature was increased. In contrast, the luminous fluxes in YAG 71, GR 84, and GR 95 using phosphor and silicone encapsulant decreased as the temperature increased. This indicated that the reason for the reduction in luminous flux with an increase in temperature was the presence of phosphor.

Although the CCT was evaluated with a tolerance of several hundred K (upper and lower limits), when LED package binning was done, the CRI was evaluated by the minimum. If the CRI falls below a reference value, the bin code becomes different. Thus, the stability of color quality according to current and temperature variations is an important quality factor.

Fig. 8 shows the changes in the CCT, CRI (R_a), R_f, and R_g in YAG 71, GR 84, and GR 95 when the supplied current is increased from 30 mA to 90 mA at a temperature of 25 °C. As the current is increased, it can be observed from Fig. 8(a) that the CCT in YAG 71 is increased; that in GR 84 and GR 95 are decreased, but their changes are relatively small. As the current is increased, it can be observed from Fig. 8(b) that the R_a in YAG 71 and GR 84



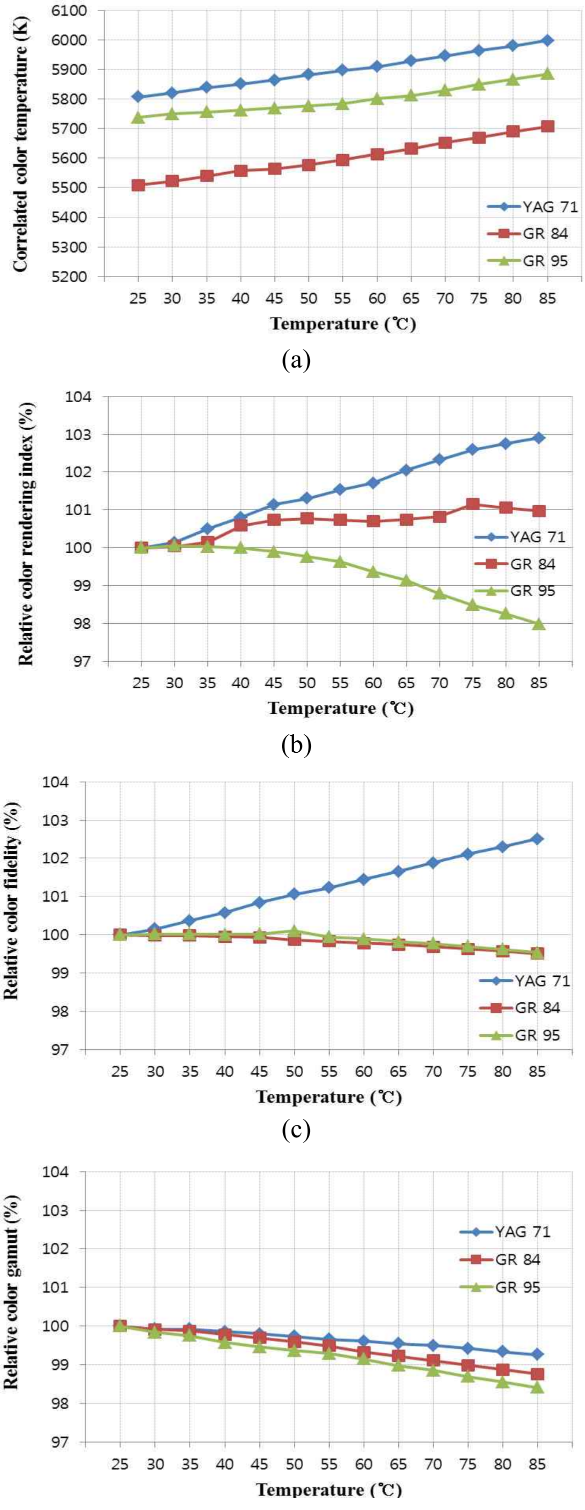
(a)

(b)

(c)

(d)

Fig. 8. Color quality of white LED according to current variation at 25 °C: (a) correlated color temperature, (b) relative color rendering index, (c) relative color fidelity, and (d) relative color gamut



(a)

(b)

(c)

(d)

Fig. 9. Color quality of white LED according to temperature variations at 60 mA : (a) correlated color temperature, (b) relative color rendering index, (c) relative color fidelity, and (d) relative color gamut

are decreased; that in GR 95 is increased, but it does not show a significant change, and is just within 1%. Fig. 8(c) shows that the R_f in GR 84 and GR 95 are not changed significantly as the current increases, whereas that in YAG 71 is reduced by more than 1%. Fig. 8(d) shows that, as the current increases, the R_g is increased for all packages. The

R_g of GR 95 is not changed significantly, whereas that of YAG 71 and GR 84 are increased by more than 1%. The color quality of YAG 71 changes significantly for a change in the current, whereas that of GR 84 and GR 95 are relatively small. This indicates that red phosphor has superior stability in terms of the changes in current [4]. It also indicates that the broader the spectrum is, the more stable it will be, in terms of changes in current. This is because of the new evaluation method that uses more CESs (99) than the eight TCSs used in the evaluation of R_a.

Fig. 9 shows the changes in the CCT, CRI (R_a), R_f, and R_g in YAG 71, GR 84, and GR 95 when the temperature is increased from 25 °C to 85 °C at a supplied current of 60 mA. As shown in Fig. 9(a), as the temperature increases, the CCT increases in all packages. The increase in the CCT in GR 95 is less than that in other packages, in a relative sense. As the temperature is increased, as shown in Fig. 9(b), the R_a in YAG 71 and GR 84 are increased, whereas that in GR 95 is decreased. Fig. 9(c) shows that the R_f in GR 84 and GR 95 do not change significantly as the temperature increases, whereas that in YAG 71 is increased by more than 2%. Fig. 9(d) shows that, as the temperature increases, the R_g is decreased in all packages; that in YAG 71 is not changed significantly, whereas that in GR 84 and GR 95 are decreased by more than 1%.

The color quality of YAG 71 changes significantly with the change in temperature, whereas those of GR 84 and GR 95 are relatively small. This indicates that, as the blue light intensity is reduced and the luminous efficacy of phosphor is reduced according to temperature variations, the spectrum changes [8]. This result proves that the problem of the existing evaluation method using eight TCSs, in which underestimates of R_a are produced when the chroma is saturated, can be overcome. It also indicates that, as the spectrum becomes broader, the color quality becomes more stable, in the case of temperature variations.

4. Conclusion

This paper described the fabrication of WLED packages with different CRIs (R_a), by using different types of phosphors (YAG:Ce, Silicate, Nitride, LuAG) for the LEDs. The color quality of the fabricated WLED was evaluated for current and temperature variation conditions. The evaluation method for color quality compared the existing CIE 13.3 and the new IES TM-30-15 methods. The characteristics of the PC-WLED are changed according to the driving conditions and the temperature environment, and the CRI (R_a) of the existing CIE 13.3 cannot be used to evaluate the user's preference. Therefore, the present study attempted to verify whether the new measures (R_f, R_g and Color vector graphics) defined in the IES TM-30-15 could compensate these problems.

The evaluation results using the IES TM-30-15 showed that the color qualities of GR 84 and GR 95, using green and red phosphors, respectively, were better than that of YAG 71 using yellow phosphor, but their luminous efficacies were lower. Furthermore, the study proved that the reason for the reduced luminous efficacy with current and temperature variations was the phosphor, and that the color qualities of GR 84 and GR 95 were more stable than that of YAG 71. Since the new evaluation method via IES TM-30-15 considered the changes in chroma accompanying the changes in current and temperature, it could overcome some of the problems in the existing evaluation method. The results of this study are expected to be useful as foundational data for selecting an optimum package for the application designs involving general lighting, by applying the improved color quality evaluation method, for different types of phosphor, operating conditions, and temperature environments of the PC-WLED.

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