

Triple-layer remote phosphor structure: a novel option for the enhancement of WLEDs' color quality and luminous flux

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The remote phosphor as a lighting structure has outstanding luminous efficiency compared to other options, such as conformal or in-cup. However, the lack of uniformity in distributed color has prevented remote phosphor from wider development. The answer to the chromatic performance enhancement that has been suggested by numerous researchers is the multi-layer configuration with two or three different types of chromatic phosphor. The research purpose is to select the best configuration for multi-chip white LEDs (WLEDs) to achieve optimal results in color quality scale (CQS), color rendering index (CRI), light output and color homogeneity. WLEDs mentioned in this paper have two distinct color temperatures, 6600 K and 7700 K. Experimental results show that the remote phosphor structure with three phosphor layers is superior in terms of color rendering, chromatic performance, and emitted light. The deviation of correlated color measured in this structure is also low, which means that the color uniformity is greatly enhanced in this multi-layer lighting structure. This result can be demonstrated by analyzing the scattering characteristics of the phosphoric layers using the Mie theory. The research findings have proven the effectiveness of the multi-phosphor configuration and can serve as a guideline to fabricate WLEDs with better performance.

Keywords: *remote-phosphor; dual-layer phosphor; triple-layer phosphor; color rendering index, luminous efficacy; Mie-scattering theory*

1. Introduction

White light-emitting diode structures (WLEDs) which possess striking qualities such as compactness, power saving, cost effectiveness, and chromatic consistency [1–6] have become a prominent element amongst light sources and thus become more and more widespread. WLEDs generate white light by integrating blue ray from LED chip with yellow ray from phosphor material [7]. Even though WLEDs have satisfying lighting performance, the insufficient light output is preventing WLEDs from expanding in solid-state lighting industry [8]. Generally, the freely dispersed coating is the most conventional technique to create WLEDs. The main materials for the coating are resin substances and phosphor particles that are combined

into a mixture before spreading on the lighting device. The reasons that freely dispersed coating is so widely applied are simplicity and cost effectiveness; however, this method results in non-uniform color distribution of the generated white light and the yellow ring phenomenon. These low optical properties in free dispersed WLEDs is a problem for high demand applications [9–12]. Therefore, another coating method using conformal diffusion of particles was suggested as a solution. The conformal coating can reduce the CCT discrepancy at far angles in WLEDs configuration and boost chromatic consistency [13]. The color quality issue might be addressed with conformal coating, yet there is a drawback of this method that causes light loss due to light reflected to the structure and impair lighting efficiency.

A solution to reduce the light loss that has been proposed by many researchers is creating

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a distance between the components within the structure of WLEDs [14–17]. The lighting efficiency is reported to increase in light extraction enhancement structure containing half-spherical lens of polymer and a phosphor layered inside [18]. In addition, structure modification such as creating vacant hole in the structure can limit the light loss by changing the direction of reflected light [19].

It is obvious that except luminous efficacy (LE), other optical properties, including rendering ability, chromatic expression and color consistency are really crucial for WLEDs. Therefore, to improve the optical characteristics of the LEDs, additional phosphor layers are added into the lighting structure to form multi-layer phosphor configuration. For the WLEDs structure with two layers, the yellow phosphor is placed under the red or green phosphor. On the contrary, in the triple-layer phosphor configuration, the yellow phosphor layer is under the red phosphoric layer, and the blue phosphor is in the middle. Along with phosphor layers arrangement, phosphor concentration management plays an equally crucial part in deciding the lumen output of the structure. However, the addition of phosphor volume causes significant damage to the generated white light, especially in lower CCTs WLEDs as the increasing amount of phosphor has more light reflected into the structure and absorbed by the phosphor layers [20–22]. Therefore, the most practical solution to enhance lighting efficiency is to increase scattering properties of yellow and blue light while preventing damage from backscattering and re-absorption.

It is not likely that the remote phosphor structure will be used to improve the optical properties of LED products due to the existence of many other methods mentioned above. Hence, this study proposes a novel approach considered as an optimal solution for manufacturers to enhance the quality of WLEDs. The results of the study provide manufacturers with a variety of options for developing specific optical properties.

2. Experimental

The first experiment consisted in boosting scattering events with green $\text{SrBaSiO}_4:\text{Eu}^{2+}$ particles.

On the other hand, the second experiment employed red phosphor $\text{Sr}_w\text{F}_x\text{B}_y\text{O}_z:\text{Eu}^{2+},\text{Sm}^{2+}$ for the extra chromatic radiation that can increase CRI and CQS of WLEDs. In the experiment, WLEDs with nine internal LED chips, shown in Fig. 1a, were used. At 1.16 W, the highest emission intensity was achieved at 453 nm wavelength. The detailed information of the WLEDs components is shown in Fig. 1b. Fig. 1c presents a single-layer remote phosphor (Y) structure with a yellow $\text{YAG}:\text{Ce}^{3+}$ phosphor layer on the surface of the LEDs. The dual phosphorylated remote phosphor (YG) structure with a red phosphor layer $\text{Sr}_w\text{F}_x\text{B}_y\text{O}_z:\text{Eu}^{2+},\text{Sm}^{2+}$ on the yellow phosphor layer $\text{YAG}:\text{Ce}^{3+}$ is shown in Fig. 1d. Fig. 1e depicts a dual-layer remote phosphor (YG) structure with a green phosphor layer $\text{SrBaSiO}_4:\text{Eu}^{2+}$ on the surface of the LEDs. The triple-layer remote layer with two phosphor layers of red $\text{Sr}_w\text{F}_x\text{B}_y\text{O}_z:\text{Eu}^{2+},\text{Sm}^{2+}$ and green $\text{SrBaSiO}_4:\text{Eu}^{2+}$ placed on the yellow $\text{YAG}:\text{Ce}^{3+}$ phosphor is demonstrated in Fig. 1f. These remote phosphor layers have a thickness of 0.08 mm. To control average correlated color temperatures (ACCTs), the concentration of $\text{YAG}:\text{Ce}^{3+}$ was varied by the change in the concentration of yellow or red phosphor. At different ACCTs in each phosphor structure, the $\text{YAG}:\text{Ce}^{3+}$ concentration is also different. This creates the difference of the scattering characteristics in LEDs, resulting in changes in optical properties.

As seen from Fig. 2, the yellow-emitting $\text{YAG}:\text{Ce}^{3+}$ phosphor reaches the highest value in Y-structure and the lowest in YRG structure at all ACCTs. Under the condition that ACCTs in the remote phosphor structures are the same, if the $\text{YAG}:\text{Ce}^{3+}$ concentration is higher, the scattering potential will be higher, resulting in reduced luminous flux. On the other hand, the balance amongst three basic colors (yellow, red, and green) that produce white light is destroyed, what can be the reason why a high $\text{YAG}:\text{Ce}^{3+}$ concentration causes a decrease in the color quality of WLEDs.

Therefore, better lumen output and chromatic performance can be obtained through balancing the three basic colors yellow, red, and green. It is possible to control the color rendering index

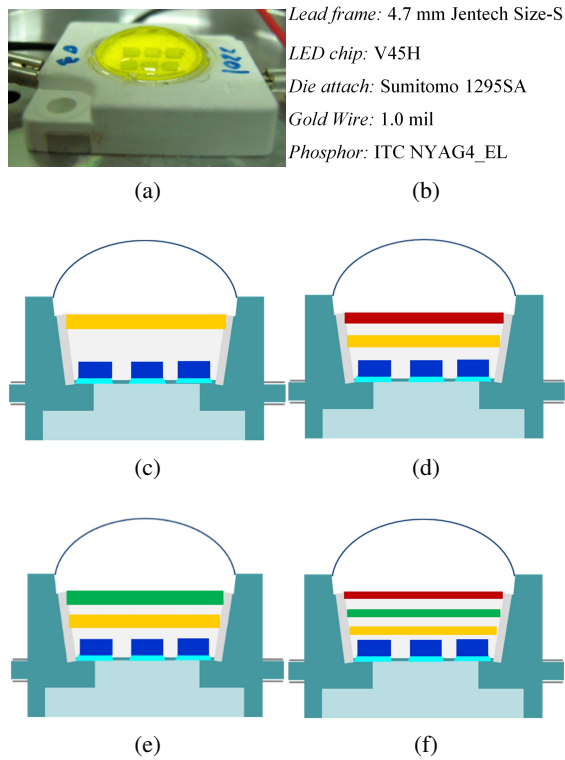


Fig. 1. Multi-layer phosphor structures of white LEDs: (a) actual MCW-LEDs and (b) its parameters; (c) single-layer phosphor, dual-layer remote phosphor with YR (d) and YG (e), and (f) triple-layer phosphor.

by increasing the amount of red light. In addition, color and luminous flux can be controlled by the green light component. Is the triple-layer phosphor structure the most advantageous in controlling optical characteristics? To answer this question, the team of researchers is constantly working on the emission spectrum to get the important information of remote phosphor structures, as displayed in Fig. 3.

There is an obvious difference in the spectra of the remote phosphor structures. The Y emitter spectra are the smallest of the three remaining remote phosphor structures in five ACCTs. It is confirmed that the Y-structure can achieve the smallest flux. In contrast, the YRG structure has the highest spectral intensity in the wavelength range of 380 nm to 780 nm. In the range of 400 nm to 500 nm, the YG structure has higher spectral intensity than the YR structure, and thus the rim of YG

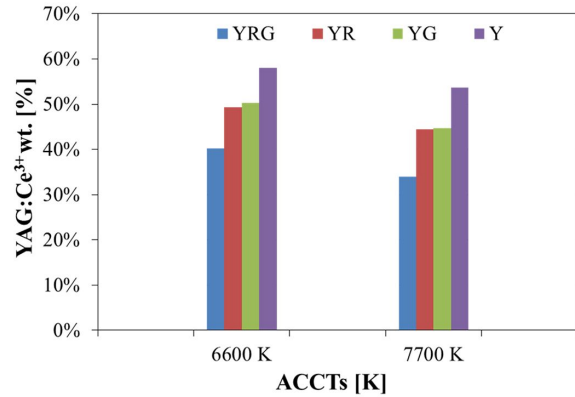


Fig. 2. YAG:Ce³⁺ phosphor concentration for each remote phosphor structure at different ACCTs.

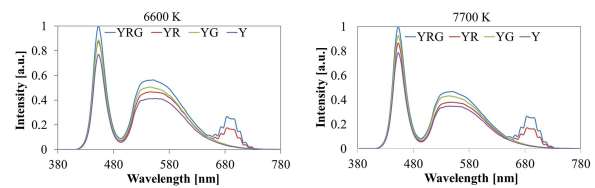


Fig. 3. Emission spectra of phosphor configurations.

may be higher than YR. However, the spectral intensity of YR is higher than that of YG in the range of 650 nm to 750 nm, which gives YR higher color rendering index than YG. The results presented in Section 3 confirm the aforementioned judgements.

3. Results and discussion

Fig. 4 shows the comparison of CRI between the remote phosphor structures. It is obvious that the YR structure achieves the highest CRI regardless of the ACCT, which is considered as a crucial factor in improving CRI for remote phosphor structures. While it is very difficult to control CRI at high ACCTs (greater than 6600 K), the YR class can do this. The YR structure enhances the CRI due to the red light component added from the red phosphor layer $\text{Sr}_w\text{F}_x\text{B}_y\text{O}_z:\text{Eu}^{2+},\text{Sm}^{2+}$.

Ranked in the second place after YR structure is the YRG structure because of its achieved CRI value. Meanwhile, the CRI in YG structure is the lowest. Although it can be argued that it is possible to select the YR structure for mass production

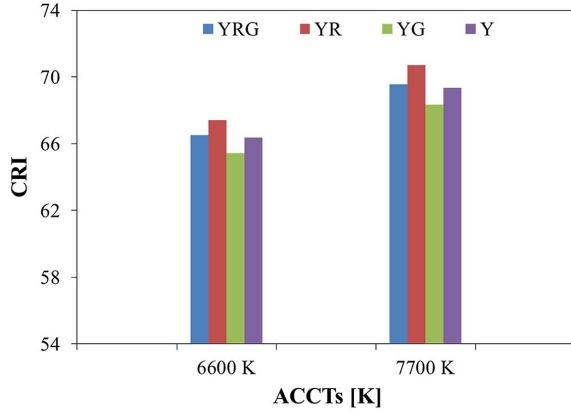


Fig. 4. Color rendering indexes of phosphor configurations corresponding to ACCTs.

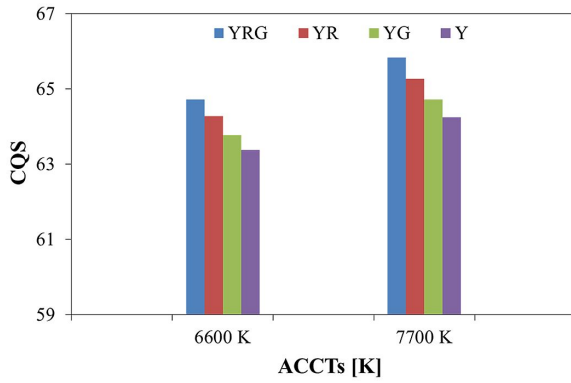


Fig. 5. Color quality scale of phosphor configurations corresponding to ACCTs.

of WLEDs with the goal of CRI, CRI is just one of the indicators of color quality. In recent years, CQS has become a research target of many studies. CQS is the combination of three elements: CRI, visual preference, and color coordinates, which makes it a big target and the most important optical indicator for evaluating color quality. In Fig. 5 we have compared the CQS of different remote phosphor structures. While YR reaches the highest CRI, YRG will achieve the highest CQS. This can be explained by the balance of three basic colors: yellow, red, and green. The higher the value of CQS, the higher the color quality. The lowest CQS is obtained in the Y structure. In general, the Y structure has an advantage in luminous flux, but it is difficult to control the color quality without the addition of

red and green light components. Despite the worse color quality, there are some advantages in production of Y structure as the process of production is simpler and the cost is reduced significantly.

Based on the results of Fig. 5, it can be confirmed that if the manufacturer's objective focuses on color quality, the YRG structure should be chosen. However, if the color quality is better, whether the luminous flux will be really effective? To answer this question, the team compared the luminescence emitted by one layer and two layers.

The following section presents the mathematical equations that were used to calculate the emitted blue light and transformed yellow light. These equations can estimate the optical properties in different situations and provide reference for development. Equation 1 and equation 2 below demonstrate how the blue and yellow radiations in phosphor configuration with layer density of 2h are estimated:

$$PB_1 = PB_0 \times e^{-2\alpha_{B1}h} \quad (1)$$

$$PY_1 = \frac{1}{2} \frac{\beta_1 \times PB_0}{\alpha_{B1} - \alpha_{Y1}} (e^{-2\alpha_{Y1}h} - e^{-2\alpha_{B1}h}) \quad (2)$$

The blue and yellow radiations in dual-layer configuration with layer density of h are computed with the following equations:

$$PB_2 = PB_0 \times e^{-2\alpha_{B2}h} \quad (3)$$

$$PY_2 = \frac{1}{2} \frac{\beta_2 \times PB_0}{\alpha_{B2} - \alpha_{Y2}} (e^{-2\alpha_{Y2}h} - e^{-2\alpha_{B2}h}) \quad (4)$$

The h is density of phosphor layer. The subscript 1 and subscript 2 refer to the single layer and double-layer remote phosphor configurations. β is the conversion coefficient for blue light converted to yellow light, γ is the reflection coefficient of the yellow light. The intensities of blue light (PB) and yellow light (PY) are obtained from light intensity of blue LED, indicated by PB_0 . α_B and α_Y are indices describing the loss of transmitted energy in blue and yellow lights during their scattering process in the respective phosphor layer.

The following formula is the comparison model of lighting efficiency of single layer configuration and double layer configuration, in which the double-layer one shows better performance:

$$\frac{(PB_2 + PY_2) - (PB_1 + PY_1)}{PB_1 + PY_1} > 0 \quad (5)$$

The Mie-theory is used in the analysis of scattering of phosphor particles, and calculating the scattering cross-section C_{ext} for circular particles. In addition, the efficiency of light power transmission can be defined by Beer law:

$$I = I_0 \exp(-\mu_{ext}L) \quad (6)$$

I_0 in this equation is the energy of incident light, L represents the density of phosphor layer (mm) and μ_{ext} is the extinction coefficient, which is expressed by: $\mu_{ext} = N_r \cdot C_{ext}$, where N_r is the number density distribution of particles (mm^{-3}). C_{ext} (mm^2) is the extinction cross-section of phosphor particles. Using MATLAB, the extinction cross-section C_{ext} of particles is computed as:

$$C_{ext} = \frac{2\pi a^2}{x^2} \sum_{n=1}^{\infty} (2n+1) \text{Re}(a_n + b_n) \quad (7)$$

$$a_n(x, m) = \frac{\psi'_n(mx) \psi_n(x) - m \psi_n(mx) \psi'_n(x)}{\psi'_n(mx) \xi_n(x) - m \psi_n(mx) \xi'_n(x)} \quad (8)$$

$$b_n(x, m) = \frac{m \psi'_n(mx) \psi_n(x) - \psi_n(mx) \psi'_n(x)}{m \psi'_n(mx) \xi_n(x) - \psi_n(mx) \xi'_n(x)} \quad (9)$$

The particles size is computed with $x = \pi D/\lambda$, a_n and b_n are the expansion coefficients with even symmetry and odd symmetry respectively, D is particle length, m is the refractive index, λ is the calculated wavelength, and $\psi_n(x)$ and $\xi_n(x)$ are the Riccati-Bessel functions. Equation 5 indicates that the use of multiple layers of the phosphor is more beneficial for luminous flux than the use of a single layer. As can be seen from Fig. 6, the Y-architecture of the four structures gets the lowest value at all ACCTs. In contrast, the luminous flux gained in the YRG structure is the highest. This eliminates the doubt that the luminous flux is obtained at the best YRG color quality. The second

rank for luminous flux is the YG structure thanks to the green phosphor $\text{SrBaSiO}_4:\text{Eu}^{2+}$. Green phosphor $\text{SrBaSiO}_4:\text{Eu}^{2+}$ helps increase the green light in the spectrum within the range of 500 nm to 600 nm. Obviously, in this wavelength range, the intensity of YG is higher than that of Y since the $\text{YAG}:\text{Ce}^{3+}$ phosphor concentration is the lowest in the YRG structure to keep the ACCT. At that time, in the YRG structure, the amount of scattered light is reduced after dropping of $\text{YAG}:\text{Ce}^{3+}$ concentration. Blue light from the LED chip easily passes through $\text{YAG}:\text{Ce}^{3+}$ layer and the other layers. In other words, the YRG structure helps the blue light from the LED chip to transform efficiently. Consequently, the YRG spectral intensity is the highest compared to other distant phosphor structures in the range of white light wavelengths. Accordingly, the luminous flux of the YRG structure reaches the peak value.

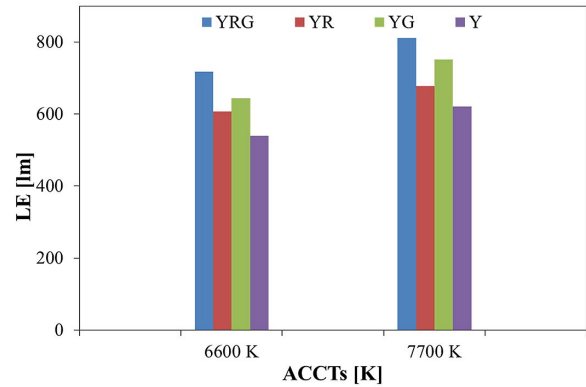


Fig. 6. Luminous flux of phosphor configurations corresponding to ACCTs.

Thus, the YRG structure can be selected by overestimating the optical properties of WLEDs including CQS and LE. However, color uniformity cannot be neglected when it comes to color quality. There are many methods for improvement of the color uniformity, including the use of advanced scattering materials, such as SiO_2 , CaCO_3 , or using conformal phosphor configurations. Although color uniformity is improved, luminous flux can be sharply reduced if these two methods are applied. The use of green $\text{SrBaSiO}_4:\text{Eu}^{2+}$ phosphor and red $\text{Sr}_w\text{F}_x\text{B}_y\text{O}_z:\text{Eu}^{2+}, \text{Sm}^{2+}$ phosphor has increased scattering properties but simultaneously

added the green or red light inside WLEDs with the purpose of producing better white light. The use of the remote phosphor structure enhances the output of the reflector that is reflected back to the LED chip. However, it is necessary to control the concentration of phosphor level to achieve the highest transmission power. It can be proved by the Lambert-Beer law in equation 6. Fig. 7 shows the comparison of color deviations between structures. The smaller the color deviation, the higher the color uniformity. It is easy to notice the smallest color difference in the case of YRG. This can be due to the scattering inside the LED package before forming the white light. The more phosphor layers, the more scattering events. As a result, the color uniformity of WLEDs improves. Obviously, there are many scattering events, in which the drop of luminous flux can occur. However, this decline is negligible compared with the benefits obtained by reduced scattering. Thus, the YRG structure achieves the best color homogeneity when the luminous flux gets the highest value. In contrast, the largest color deviation was observed in Y-structure at all ACCTs.

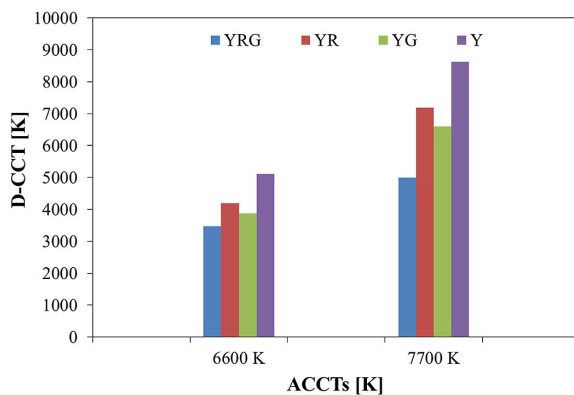


Fig. 7. Corelated color temperature deviation (D-CCT) of remote phosphor configurations corresponding to ACCTs.

4. Conclusions

In conclusion, this article has compared the optical effects of four distinct structures Y, YG, YR, and YRG at five different ACCTs values. Green $\text{SrBaSiO}_4:\text{Eu}^{2+}$ phosphor and red

$\text{Sr}_w\text{F}_x\text{B}_y\text{O}_z:\text{Eu}^{2+},\text{Sm}^{2+}$ phosphor were used in the simulation. In addition, the results of the study were verified by the Mie theory and the Lambert-Beer law. Accordingly, the coating of the green $\text{SrBaSiO}_4:\text{Eu}^{2+}$ phosphor implements blue light to improve the color uniformity and photon emission. Therefore, the YG structure reaches better optical and color uniformity than the YR structure. CRI and CQS can be improved by increasing the red light component through the red layer $\text{Sr}_w\text{F}_x\text{B}_y\text{O}_z:\text{Eu}^{2+},\text{Sm}^{2+}$ phosphor. As a result, the YR structure reaches higher CRI and CQS than YG. It is obvious to see that the color quality depends on the balance between the three primary colors yellow, green, and red. The YRG structure can satisfy the controlling of these three colors. Furthermore, the reflective degradation of the YRG layer helps to increase the flux of this configuration. The evidence is that the highest feasible luminaire is also to achieve in the YRG structure. Based on the results obtained in this study, the manufacturers can easily select a suitable structure for improving the quality of WLEDs.

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