SELECTING A SUITABLE REMOTE PHOSPHOR CONFIGURATION FOR IMPROVING COLOR QUALITY OF WHITE LED

Hsiao-Yi LEE[1], *Phan Xuan LE*[2], *Doan Quoc Anh NGUYEN*[3,*]

[1]Department of Electrical Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan
[2]National Key Laboratory of Digital Control and System Engineering, Ho Chi Minh City, Vietnam
[3]Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

*Corresponding Author: Doan Quoc Anh NGUYEN (Email: nguyendoanquocanh@tdtu.edu.vn)

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Abstract. *When compared with two conformal phosphor and in-cup phosphor structures, the remote phosphor structure has higher luminescent performance. However, it is difficult to control the color quality of the remote phosphor structure, so it has become a research target in recent years. So far, there are two remote phosphor structures used to improve color quality including dual-layer phosphor configuration and triple-layer phosphor configuration. This study suggests using those two configurations to make multi-chip white LEDs (WLEDs) that can achieve adequate values in color rendering index (CRI), color quality scale (CQS), luminous efficacy (LE) and color uniformity. WLEDs with color temperature of 5600 K are applied. Research results show that the triple-layer phosphor configuration is superior in CRI, CQS, LE. Besides, the color deviation decreases significantly, meaning that the color homogeneity increases with the triple-layer phosphor configuration. This can be demonstrated by analyzing the scattering characteristics of phosphor classes through Mie theory, thus making the research results more reliable and valuable for producing quality WLEDs.*

Keywords

Remote-phosphor, Dual-layer phosphor, Triple-layer phosphor, Color rendering index, Luminous efficacy, Mie-scattering theory.

1. Introduction

Phosphor-converted white light-emitting diodes (WLEDs) are a potential light source because of their small size, high energy efficiency, reasonable cost, and color stability [1-4]. WLEDs apply the principle of complementary colors: Blue light from a blue chip is linked with yellow light from phosphor [5]. WLEDs have a high probability of being applied in solid-state lighting, but their luminous efficiency must be strengthened [6]. Generally, a freely dispersed coating is the most familiar technique utilized to construct white light. In this process, the transparent encapsulated resin is combined with phosphor powder and is dispersed on the phosphor package. Although this approach allows the thickness of the phosphor layer to be controlled easily and reduces much of the cost, it does not produce high-quality WLEDs [7]. Therefore, the conformal coating method can be used as an alternative. This method distributes colors uniformly, resulting in angular homogeneity of correlated color temperature (CCT) [8]. However, the disadvantage of a conformal phosphor structure is the backscattering effect, which reduces luminous efficiency. Previous studies have proved the concept of separating the chip and the phosphor layer of remote phosphor structures [9, 10]. The enhanced light extraction internal reflection structure, which uses a polymer hemispherical shell lens with an interior phosphor coating, is known to increase extraction efficiency [11]. Furthermore, an air-gap embedded structure can enhance luminous efficiency by reflecting downward light [12]. Obviously, in addition to luminous efficacy (LE), other optical characteristics including color rendering index (CRI), color quality scale (CQS) and color uniformity are all so extremely important for WLEDs. Therefore, two improved remote phosphor structures were applied to improve the optical properties of LEDs including dual-layer phosphor configuration and triple-layer phosphor configuration. For dual-layer phosphor configuration, the yellow phosphor layer below and above is the phosphor red or green layer. For the triple-layer phosphor configuration, the yellow phosphor layer below and above is the red phosphor layer, the middle is the green phosphor. In addition to the structure of the package, the concentration of phosphor plays an important role in luminous efficiency. The re-absorption failure in the phosphor layer is obtained when the phosphor concentration increases. Therefore, device luminous efficiency would be lessened, specifically at lower CCTs [13]. Therefore, it is essential to enhance the emission of blue and yellow rays and reduce the amount of light lost from backscattering and reflection. It is difficult for manufacturers to choose a remote phosphor structure to improve the optical properties of their LED products due to the many proposed methods mentioned above. Prior research papers only focus on a few phosphor configurations and lighting performance indicators to come up with a solution to improve WLED, which sometimes limits the researchers' overview and the ability to find the best solution available. Therefore, this article wants to emphasis on diversity and application efficiency by considering different types of phosphor structures with distinct packaging order and evaluate their performance through the results from practical experiments that assess various criteria. As a result, this study can propose the optimal choice to improve all individual features so that producers can choose an optimal plan to improve the quality of WLEDs to correspond with their personal goals.

2. Simulation

The first idea of the study is to use the $YAl_3B_4O_{12}$:Ce^{3+},Mn^{2+} phosphor green layer to increase the green light component in WLEDs, leading to increased luminous flux. The second idea is to use the red phosphor layer $MgSr_3Si_2O_8$:Eu^{2+},Mn^{2+} to increase the red light component in WLEDs, leading to increased CRI and CQS. $YAl_3B_4O_{12}$:Ce^{3+},Mn^{2+} and $MgSr_3Si_2O_8$:Eu^{2+},Mn^{2+} particles, with many outstanding characteristics such as high quantum efficiency and stability at high temperature, are known as a type of yellow-green phosphor and become more and more popular. Moreover, $YAl_3B_4O_{12}$:Ce^{3+},Mn^{2+} and $MgSr_3Si_2O_8$:Eu^{2+},Mn^{2+} phosphor are applied particularly for very high-loading and long lifetime fluorescent lamps. $YAl_3B_4O_{12}$:Ce^{3+},Mn^{2+} glows yellow-green at a peak wavelength at 545 nm. Meanwhile, $MgSr_3Si_2O_8$:Eu^{2+},Mn^{2+} emits red light with peak wavelength at 681 nm.

The condition for these phosphors to be applied is that they must have a spectrum that matches with the blue light emission wavelengths from the LED chip. Before performing any optical simulation of $YAl_3B_4O_{12}$:Ce^{3+},Mn^{2+} and $MgSr_3Si_2O_8$:Eu^{2+},Mn^{2+}, the synchronization between the absorption spectrum of these phosphor types and the emission spectrum from the blue chip must be guaranteed to ensure accuracy. Input parameters, such as phosphor concentration, phosphor particle size, excitation spectrum, absorption spectrum, and phosphor emission spectrum, need to be accurately determined by experiments. Among the five

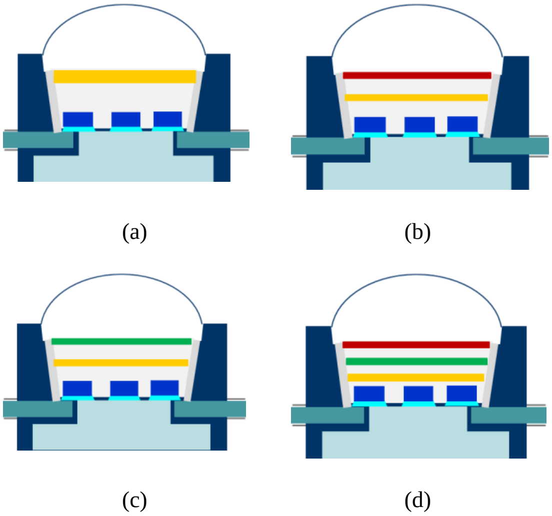

Fig. 1: (a) Single-layer phosphor structure with yellow phosphor, (b) dual-layer remote structure with yellow-red phosphors, (c) dual-layer remote structure with yellow-green phosphors and (d) triple-layer structure with yellow-green-red phosphors.

parameters above, the concentration and size of phosphor are the unknown numbers to achieve the highest color and luminous flux quality of the LED. Spectral parameters are constant. Based on the results of the previous studies [8-14], the diameter of phosphor particles is fixed at an average of 14.5 μm.

In this study, WLEDs with 9 internal chips are used. The output of each of these blue chips is 1.16W, with a peak wavelength emitted at 453 nm. Figure 1(a) shows the single-layer remote phosphor (Y) structure with a yellow phosphor YAG:Ce^{3+} on the surface of the LEDs. Figure 1(b) presents the dual-layer remote phosphor (YR) structure with a red phosphor layer MgSr$_3$Si$_2$O$_8$:Eu^{2+},Mn^{2+} on the yellow phosphor YAG:Ce^{3+}. Figure 1(c) presents the dual-layer remote phosphor (YG) structure with a layer of green phosphor YAl$_3$B$_4$O$_{12}$:Ce^{3+},Mn^{2+} above the yellow phosphor YAG:Ce^{3+} and the LEDs chips. The triple-layer remote structure that has a green phosphor YAl$_3$B$_4$O$_{12}$:Ce^{3+},Mn^{2+} between a red phosphor layer MgSr$_3$Si$_2$O$_8$:Eu^{2+},Mn^{2+} on top and yellow phosphor layer YAG:Ce^{3+} below is called the YRG structure and is shown in Figure 1(d). These remote phosphor layers are 0.08 mm thick.

To maintain the average correlation color temperature average correlation temperature (ACCTs), YAG:Ce^{3+} concentration changes when changing the phosphor yellow or red phosphor concentration. At each different ACCT for each phosphor structure, YAG:Ce^{3+} concentration is also different. This makes the difference in scattering properties in WLEDs, resulting in differences in optical properties.

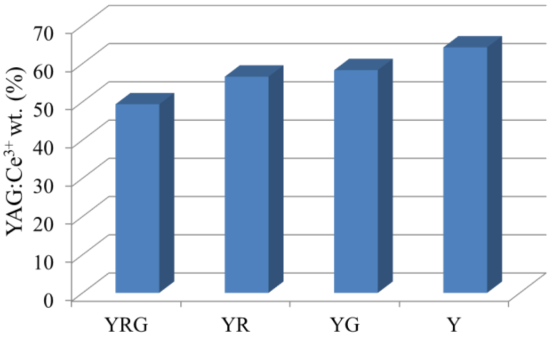

Fig. 2: YAG:Ce^{3+} concentration corresponds to remote phosphor structures.

In Figure 2, it is easy to see that the highest yellow-emitting YAG:Ce^{3+} phosphor concentration is in the Y structure and the lowest is in the YRG structure. Regarding to the remote phosphor structures, the higher the YAG:Ce^{3+} concentration, the higher the scattering ability, resulting in reduced luminous flux. On the other hand, the imbalance between the three primary colors that produce white light: yellow, red and green appears when the YAG:Ce^{3+} concentration is high, causing a decrease in color quality of WLEDs. Therefore, in order to improve the luminous flux and color quality of WLEDs, the backscattering effect must be reduced and the three basic colors yellow, red and green must be balanced. The color rendering index can be controlled by increasing the red light component. Besides, color homogeneity can be controlled by adding the green light component. According to the findings and requirements above, it seems that triple-layer phosphor structure is the most favorable structure in controlling optical properties. However, there is another crucial aspect that need to consider before concluding, emission spectra.

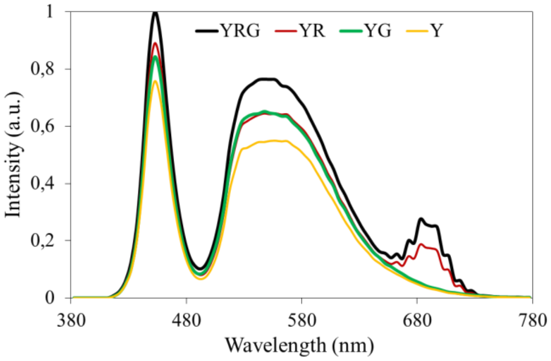

Fig. 3: Emission spectra corresponds to remote phosphor structures.

There are significant differences in emission spectra among the four remote phosphor structures. The Y-emission spectrum has the smallest intensity compared to the other three remote phosphor structures. This confirms that the Y structure achieves the smallest luminous flux. In contrast, the YRG structure has the largest spectral intensity in the wavelength range of 380 nm - 780 nm. In the range of 400 nm - 500 nm, YG structure has a higher spectral intensity than YR structure so YG's luminous flux can be higher than YR. However, YR's emission spectral intensity is higher than YG's in the range of 650 nm - 750 nm, which helps YR achieves higher color rendering index than YG. However, to confirm the findings mentioned above, it is necessary to consider the results achieved in section 3.

3. Results and discussion

Figure 4 shows the CRI comparison between remote phosphor structures. It is easy to see that the YR structure achieves the highest CRI. The outstanding CRI value in YR structure is benefited by the red light component added from the red phosphor layer $MgSr_3Si_2O_8$:Eu^{2+},Mn^{2+}. The second position in the CRI value achieved is the YRG structure. Meanwhile, CRI is the lowest in YG structure. These results confirm that YR is the best structure for mass production of WLED that focuses on CRI.

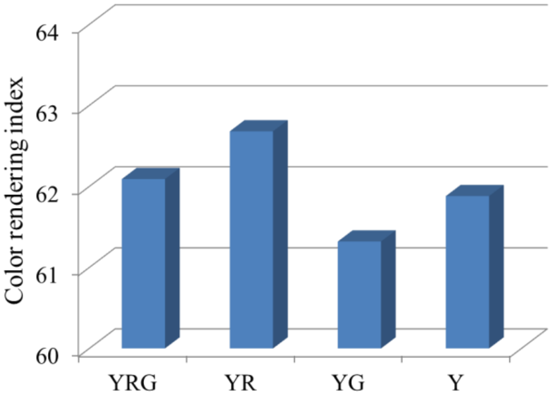

Fig. 4: Color rendering indexes of remote phosphor structures.

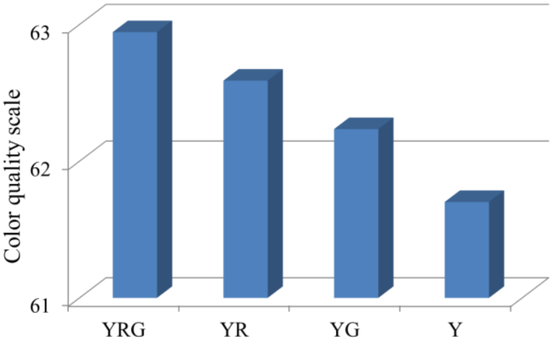

Fig. 5: Color quality scale of remote phosphor structures.

However, CRI is just one of the color quality indicators. In recent years, CQS has become the research target of many studies. CQS is a combination of 3 elements: CRI, person's preference and color coordinates. With the coverage of these three factors, CQS becomes a big target and "seems" to be the most important indicator to assess color quality. Thus, it can be concluded that the higher the CQS value is, the higher the color quality becomes. In this study, the CQS values of the remote phosphor structures are compared in Figure 5. If the YR reaches the highest CRI, the YRG reaches the highest CQS. This can be explained by the balance of 3 basic colors yellow, red and green. Meanwhile, the CQS is the lowest in the Y structure. In general, the Y structure has a high luminous flux, but it is difficult to control the color quality due to the lack of red and green light components. Despite the disadvantage in color quality, Y structure has advantages in production. The production procedure for Y structure WLED is simpler than the rest, which also reduces the production costs.

Based on the result of Figure 5, it can be confirmed that if the manufacturer's goal is color quality, it is recommended to select YRG structure. However, there is an assumption that the luminous flux will be affected if the color quality is better. The comparison between the emitted luminous flux between the single-layer and dual-layer structures will help to demonstrate this issue. This part will show and describe the mathematical model of the transmitted blue light and converted yellow light in the double-layer phosphor structure, from which a notable advancement of LED efficiency can be achieved. The transmitted blue light and converted yellow light for single layer remote phosphor package with the phosphor layer thickness of $2h$ are expressed as follows:

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

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

The transmitted blue light and converted yellow light for double layer remote phosphor package with the phosphor layer thickness of h are defined as:

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

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

where h is the thickness of each phosphor layer. The subscript "1" and "2" are used to illustrate single layer and double-layer remote phosphor package. β presents the conversion coefficient for blue light converting to yellow light. γ is the reflection coefficient of the yellow light. The intensities of blue light (PB) and yellow light (PY) are the light intensity from blue LED, indicated by PB_0. α_B, α_Y are parameters describing the fractions of the energy loss of blue and yellow lights during their propagation in the phosphor layer respectively.

The lighting efficiency of pc-LEDs with the double-layer phosphor structure enhances considerably compared to a single layer structure:

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

The scattering of phosphor particles was analyzed by using the Mie-theory. In addition, the scattering cross section C_{sca} for spherical particles can be computed by the following expression through applying the Mie theory. The transmitted light power can be calculated by the Lambert-Beer law:

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

In this formula, I_0 is the incident light power, L is the phosphor layer thickness (mm) and μ_{ext} is known to be the extinction coefficient, which can be expressed as: $\mu_{ext} = N_r.C_{ext}$, where N_r is as the number density distribution of particles (mm^{-3}). C_{ext} (mm^2) is the extinction cross-section of phosphor particles.

Equation 5 demonstrates that using multiple phosphor layers is more beneficial to luminous flux than a single layer. Obviously, this is illustrated in the results of Figure 6, the structure Y reaches the lowest luminous flux out of the four structures. In contrast, the highest luminous flux is achieved in the YRG structure. This eliminates any doubt about YRG lumen output when its color quality is the best. The second place in terms of the usefulness in luminous flux development is the YG structure thanks to the green phosphor $\mathrm{YAl_3B_4O_{12}{:}Ce^{3+},Mn^{2+}}$. Green phosphor $\mathrm{YAl_3B_4O_{12}{:}Ce^{3+},Mn^{2+}}$ helps to increase green light composition and increase spectra intensity in the wavelength range of 500 nm - 600 nm. Clearly in this wavelength range, YG's intensity is greater than YR and Y. Due to the smallest $\mathrm{YAG{:}Ce^{3+}}$ concentration in the YRG structure that can keep the ACCT, the YRG structure reduces the amount of reflected light after the $\mathrm{YAG{:}Ce^{3+}}$ concentration decreases. Blue light rays from LED chips are easily transmitted straight through the $\mathrm{YAG{:}Ce^{3+}}$ layer to other layers. In other words, the YRG structure helps blue light energy from the LED chip to convert efficiently. Therefore, the YRG spectral intensity is the highest compared to other remote phosphor structures in the same white light wavelength range. Accordingly, the luminous flux of the YRG structure also reached the highest level.

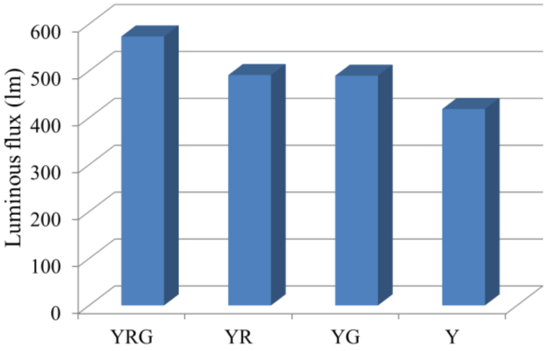

Fig. 6: Luminous flux of remote phosphor structures.

Thus, the YRG structure can be selected for the superior optical properties of WLEDs including CQS and LE but cannot be ignored in color homogeneity when it comes to color quality factor. There are many methods to improve color homogeneity including methods of using advanced scattering particles such as SiO_2, $CaCO_3$,... or using conformal phosphor configuration. Although the color uniformity is improved, luminous flux can be significantly reduced if the two methods above are applied. The use of green $YAl_3B_4O_{12}:Ce^{3+},Mn^{2+}$ phosphor and red $MgSr_3Si_2O_8:Eu^{2+},Mn^{2+}$ phosphor is not only to increase the scattering properties but also to add a green or red light component inside WLEDs to produce more white light. The use of a remote phosphor structure enhances the luminous flux emitted by reducing reflections back to the LED chip. However, it is necessary to control the phosphor layer concentration to achieve the highest transferred energy. This can be proved by Lambert-Beer law's law in expression 6.

Figure 7 shows the comparison of color deviation between structures. The smaller the color deviation is, the higher the color homogeneity becomes. It is easy to see that the color deviation of YRG is the smallest, which can be explained by the scattering inside the LED package before forming white light. The more phosphor layers, the more scattering events, leading to increased color uniformity of WLEDs. Of course, when there are many scattering events, the loss of luminous flux can occur. However, this reduction is negligible compared to the benefit obtained when the backscattering is reduced. Therefore, the YRG structure achieves the best color uniformity with the highest luminous flux. In contrast, the highest color deviation is expressed in the Y structure.

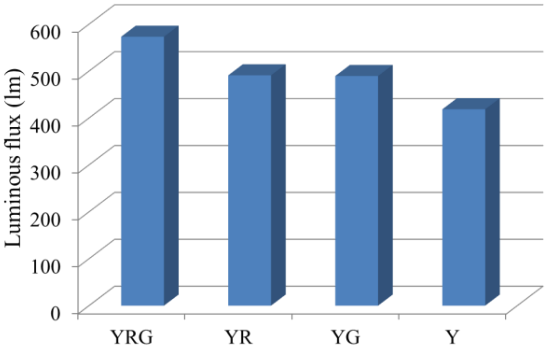

Fig. 7: Correlated color temperature deviation (D-CCT) of remote phosphor structures.

4. Conclusions

This paper compares the optical performance of four structures, Y, YG, YR and YRG. Green-emitting $YAl_3B_4O_{12}:Ce^{3+},Mn^{2+}$ phosphor and red-emitting $MgSr_3Si_2O_8:Eu^{2+},Mn^{2+}$ phosphor are used in the simulation process. In addition, the study results were verified by the Mie theory and the Lambert-Beer law. According to the results, adding green $YAl_3B_4O_{12}:Ce^{3+},Mn^{2+}$ phosphor adds green light that improves color homogeneity and luminous flux. Therefore, the YG structure achieves better optical flux and color uniformity than the YR structure. CRI and CQS can be improved when increasing the red light component through the red $MgSr_3Si_2O_8:Eu^{2+},Mn^{2+}$ phosphor. As a result, YR structure achieves higher CRI and CQS than YG. The color quality depends on the balance between the three primary colors yellow, green and red. YRG structure can satisfy the requirements to control these 3 colors. In addition, the reduced light loss due to reflection of YRG leads to a significant increase in the luminous flux of this configuration. The evidence is that the highest luminous flux is also achieved in the YRG structure. Based on the results of this study, producers can easily choose a suitable structure for quality improvement of WLEDs.

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About Authors

Doan Quoc Anh NGUYEN was born in Khanh Hoa province, Vietnam. He has been working at the Faculty of Electrical and Electronics Engineering, Ton Duc Thang University. Quoc Anh received his PhD degree from National Kaohsiung University of Applied Sciences, Taiwan in 2014. His research interest is optoelectronics.

Phan Xuan LE was born in Binh Dinh province, Vietnam. He has been working at the Faculty of Electrical and Electronics Engineering, HCMC University of Food Industry. He received his Ph.D. degree from Kunming University of Science and Technology, China in 2015. His research interest is power system; optoelectronics.

Hsiao-Yi LEE was born in Taiwan. He has been working at the Department of Electrical Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan. His research interest is optoelectronics.