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The options in remote phosphor structure for better white LEDs color quality

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ABSTRACT

The WLEDs configuration with remote phosphor layers has higher luminescent performance than WLEDs with dispense coating or conformal coating and is applied for many modern devices. However, managing the chromatic performance of lighting structure with remote phosphor materials is a challenging objective that demands more research. This has inspired the usage of multi phosphor configurations with distance in between the layers to improve color quality. The results of this manuscript can support the manufacturers in choosing the optimal configuration for optical performance in LEDs devices with more than one phosphor material. The simulated model used in the experments is 6500 K CCT WLEDs, which results show the triple-layers structure is more favorable in terms of color quality and light output. Besides, a notable reduction occurs in color deviation means that chromatic stability is also enhanced in WLEDs with three phosphor layers. Through experimental results, which were confirmed by the Mie-scattering theory, this research offers valuable approach and details to produce better WLEDs.

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1. INTRODUCTION

Lighting devices using LEDs and phosphor material to fabricate white light (WLEDs) contains many remarkable traits such as power saving, cost effective, color consistency, and smaller in size, are perceived as a potential light source [1-4]. The WLEDs work base on the additive color principle, for example, the combination between the yellow light of phosphor with blue light comes from a blue chip [5]. If the lighting efficiency of WLEDs improves, there is a good chance that they are usable in solid-state lighting [6]. The WLEDs are often created by diffusing the phosphor particles onto the LEDs to form a layer. This process will mix the transparent encapsulated resin and the phosphor powder then dispersed on the phosphor package. The advantage of this method is the control over the thickness of the phosphor layer and lowered cost, however, the product is not a high-quality WLEDs [7-9]. As a result, the conformal coating method is a replacement in this situation. The purpose of this method is to distribute colors uniformly and improve the angular color uniformity of CCT [10-13]. However, the light output of conformal coating configuration is weakened by backscattering effect, therefore, the luminous efficiency unable to reach the best result. The approach of isolating the components of the remote phosphor WLEDs has already been mentioned in prior researches with different variations [14-16]. For example, the usage of epoxy hemispherical glass coated with phosphor on the inside amplifies the extracted light by enhancing internal reflection of the structure [17]. Not to mention the luminous efficiency also benefits from the air-gap embedded structure because of the downward light reflection characteristic [18-20]. It is obvious that besides luminous efficacy (LE), other chromatic quality indicators such as color stability, rendering ability are also critical targets to WLEDs. Therefore, modifications such as adding more phosphor material to the remote structure are expected to bring desirable alterations and improve these optical properties of WLEDs [21-23]. The arrangement of phosphor layers in remote structure with two phosphor materials is yellow phosphor below red or green phosphor, while in structure with three phosphor layers the red phosphor is at the top below are green phosphor and yellow phosphor [24, 25]. The concentration of phosphor layer is also an impactful element alongside model arrangement. The additional phosphor materials can cause the re-absorption in the phosphor layer and leads to lower luminous efficiency, particularly in low CCTs. In order to address this problem, the loss of light due to backscattering and reflection must be lowered and the emission of blue and yellow lights needs to improve. Choosing one single remote phosphor structures to improve optical properties for WLEDs from all of the available structures above is a difficult task for the manufacturer. Therefore, this research serves the purpose of offering manufacturers with an optimal choice to enhance WLEDs quality to their desire. The results of this research will demonstrate detailed plans to develop specific optical features.

2. SIMULATION DETAIL

The WLEDs equipped with 9 LED chips inside are used for reference in this research. Each blue at peak wavelength emits an output of 1.16W. Figure 1 (a) demonstrate the traditional structure (Y) contains a layer of yellow phosphor YAG:Ce^{3+} put on top of LEDs chip. Figure 1 (b) is the remote phosphor structure (YR) with two layers, one is red phosphor layer $LiAl_5O_8$:Fe^{3+} and the other below is yellow YAG:Ce^{3+}phosphor layer. The other remote phosphor (YG) with double layers with the green (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb phosphor placed above LED chips appears in Figure 1 (c). The only triple-layer remote structure with a green phosphor (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb in between two other phosphor layer is visualized in Figure 1 (d).

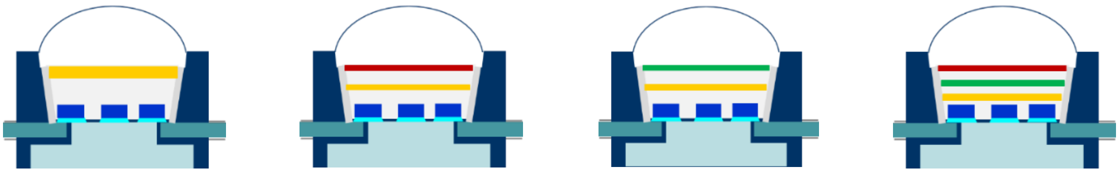

Figure 1. Illustration of multi-layer phosphor structures of white LEDs: (a) Single-layer phosphor, Dual-layer remote phosphor with YR (b) and YG (c), and (d) triple-layer phosphor

The first idea of this research is using a green phosphor layer (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb to enhance the green radiation of WLEDs and promote the emitted light from the structure. The second idea revolves around employing a red phosphor layer $LiAl_5O_8$:Fe^{3+} to stimulate an increase in CRI and CQS with red particles from the phosphor. The article elaborates in details the extent which the presence of $LiAl_5O_8$:Fe^{3+} affects the WLEDs optical properties according to the phosphor concentration. With remarkable features including high quantum efficiency and high temperature consistency, the phosphor particles that emits yellow-green light such as (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb and $LiAl_5O_8$:Fe^{3+} have acquired much attention. That is the reason why (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb and $LiAl_5O_8$:Fe^{3+} are especially used in heavy duty and high durability fluorescent lamps. (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb at peak wavelength of 546 nm emits a green light. The presence of the ion Eu^{2+} benefits (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb by enhancing the luminous efficacy. As the same time, $LiAl_5O_8$:Fe^{3+} emits red light at the peak wavelength of 681 nm. The ideal setup that allow these phosphors to excel is the one that can adjust phosphor radiation and light chips radition to discharge at the same wavelengths. This means the phosphor materials and the chip should have as much common emission wavelengths in their spectra as possible. The range of $LiAl_5O_8$:Fe^{3+} absorption spectrum covers from 320 nm to 480 nm is an enhancement in collecting chromatic radiation out of other wavelength ranges such as yellow since the LED chip is not the only component that emits light. The green phosphor

(Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb with a vast absorption spectroscopy, which ranges from 200 nm to 400 nm, is also an appropriate material. Before conducting the stimulation of (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb and $LiAl_5O_8:Fe^{3+}$, the input numbers must be measured correctly through different experiments including the concentration of phosphor, size of phosphor particles, excitation spectrum, absorption spectrum, phosphor emission spectrum. The amount of phosphor and their particles magnitude out of the five indicators are the required factors to obtain the highest values in color quality and luminescent flux for WLEDs. The indexes related to the spectra are constants. As the results from previous research suggest, the diameters for phosphor particles revolve around an average of 14.5 µm.

The density of each phosphor layer in the remote structure is predetermined at 0.08 mm. The average correlated color temperature (ACCT) is an important index that must be stabilized by changing the concentration of YAG:Ce^{3+}. The concentration of YAG:Ce^{3+} is adjusted in every phosphor configuration to stabilize the ACCT while performing the experimentes. This form a distinction in the scattering characteristic of the LEDs resulting in a variety of differences in optical properties. The percentages of yellow-emitting phosphor YAG:Ce^{3+} in each remote phosphor structure are presented in Figure 2

From Figure 2, it appears that yellow-emitting YAG:Ce^{3+} phosphor percentage among the phosphor structures is different with the Y structure has the most yellow phosphor and YRG structure the least. Regarding the same ACCT but with the remote phosphor structure, if the concentration of YAG:Ce^{3+} rises up the backscattering effect also increases which damages the luminous flux. On the other hand, when the concentration level of YAG:Ce^{3+} is high, the imbalance among the three primary colors contribute to the fabrication of white light: red, yellow and green will appear and causes the color quality to decrease. Therefore, preventing light loss and equalize the proportions of chromatic phosphor in the structure can lead to enhancement in resulted light and chromatic output. The YRG structure which has three chromatic phosphor layers that can effectively balance the primary colors, enhance the color rendering ability with red particles, and improve color uniformity as well as lumen output with green particles, seems to be the ideal solution. So is the phosphor structure containing three distinct chromatic layers the optimal configuration in controlling optical properties? To verify this theory, we need to examine other crucial aspects of an lighting configuration such as the emission wavelength range, which is demonstrated in Figure 3.

The differences between emission spectra of remote phosphor structures are definitely obvious. The Y structure with the lowest intensity index among others means that the emission spectrum from this structure is at minumum. In contrast, YRG structure, with emission spectrum from 380-780 nm, produces the most intensity. The YG and YR structures intensity depends on the wavelength range, from 400-500 nm spectral intensity in YG is higher than YR, therefore YG emission spectrum is also greater in comparision to YR. On the other hand, YR in the band from 650-750 nm has higher intensity, which means the color rendering of YR in this emission spectrum is more effective than YG. In order to approve all the conclusions above, part 3 will focus on testing and giving results.

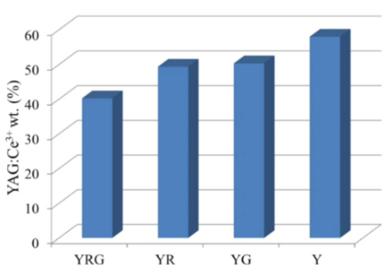

Figure 2. YAG:Ce^{3+} concentration corresponding to the remote phosphor confifurations

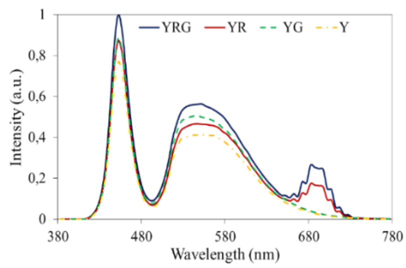

Figure 3. Emission spectra of the phosphor configurations

3. RESULTS AND DISCUSSION

Figure 4 demonstrates the measured color rendering index (CRI) of all lighting configurations. It is obvious that YR structure achieves highest CRI. This is an important result when it comes to improving CRI in remote phosphor structures. Although controlling the CRI in high ACCT is exceptionally difficult, the YR structure can undertake this task. The YR structure with red phosphor layer $LiAl_5O_8:Fe^{3+}$ that provide the structure with additional red particles achieves better color rending index (CRI). YRG is second place in term of CRI achieved. Meanwhile, CRI produced by YG structure is the lowest. This result suggests that applying YR structure to serial manufacturing of WLEDs with CRI as the main goal is the optimal choice. The CRI is a popular quality indicator but not enough to conclude the performance of lighting device just based on CRI. The CQS, which examines three features including CRI, observer choice, and color coordination, has risen up and were applied for quality assessment in recent research. With the coverage over these three aspects, CQS seemingly turns out as a vital point and is regarded as the most crucial indicator to evaluate color quality. CQS values of the configurations were calculated and presented in Figure 5. If CRI is highest in YR structure then CQS is reaches its peak in YRG structure which is a result of better balance between chromatic lights yellow, red and green. The high CQS value ensure the good chromatic performance of WLEDs. Meanwhile, the Y structure with poor CQS in comparision to other structures is struggling to manage the chromatic attribute of emitted light due to the lack of chromatic sources, however, this structure presents great value to the lumen output. Despite the drawback in color quality, Y structure still excels in manufacturing due to simpler producing process compare to other structure and relatively low cost.

Based on the results in Figure 5, the YRG structure is a perfect fit for WLEDs with high color quality demands. However, does the increase in color quality affect the luminous flux? A comparison between the first layer and second layer was used to answer the previous question. The mathematical equation to calculate the blue and yellow light yielded from WLEDs with two phosphor layers is presented in this part. The results provide valuable information for better understanding of WLEDs mechanism and enhancing methods. The amount of emitted blue light and modified yellow light in single phosphor package with $2h$ phosphor density are shown below:

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

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

In dual-phosphor remote WLEDs with an h phosphor layer density, the amount of emitted blue light and modified yellow light are expressed as:

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

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

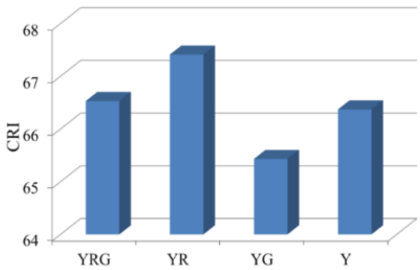

Figure 4. Color rendering indexes of the phosphor configurations

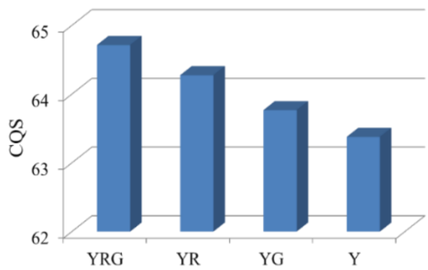

Figure 5. Color quality scale of phosphor configurations

The h denotes phosphor density (mm). The subscript "1" indicates WLEDs with single phosphor structure and "2" indicates WLEDs with dual-phosphor remote structure. The β stands for the rate of internal conversion from blue transforms to yellow light. The reflection coefficient of the yellow light is illustrated by γ. The radiation intensities of LED chip including the blue light intensity (PB) and yellow light intensity (PY) are represented by PB_0. The blue and yellow light energy lost during the spreading process in the phosphor layer are indicated by α_B; α_Y respectively. The WLEDs in double-layer phosphor structures have their luminous efficacy improved significantly in comparison with the single layer structure ones:

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

The utilization of the Mie-theory is to inspect the amount of light scatters from phosphor particles. Besides, the Mie theory also contributes to the calculation of scattering cross section C_{sca} for spherical particles. The Lambert-Beer law measures the light power emitted:

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

I_0, is the incident radiation energy, while the density of phosphor material is L (mm) and μ_{ext} for the extinction coefficient, which can be calculated with the formula: $\mu_{ext} = N_r.C_{ext}$, with N_r the number density distribution of particles (mm^{-3}) and the extinction cross-section of phosphor particles C_{ext} (mm^2).

From the results of (5), the multi-layer phosphor structure is clearly more beneficial to the light output capacity than the structure with only one layer. This finding is verified by the results of measured luminous fluxes in Figure 6. According to the graph, Y structure has the lowest amount of emitted light among structures. YRG structure, on the contrary, achieves the highest value in luminous flux. This clear all the questions revolve around the impact of YRG structure on the luminous flux since it has the best color quality. The YG structure is the second best in terms of lumen output due to the addition of green light component from the green (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb phosphor. The luminous flux within the wavelength from 500-600 nm benefit from the green phosphor (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb. It is obvious that the intensity of YRG structure in these wavelengths is greater than YG and Y. Therefore, YAG:Ce^{3+} concentration level in YRG structure is dropped to the lowest among all structures to maintain ACCT and the backscattering effects also decrease after the concentration of YAG:Ce^{3+} in YRG declined. The blue light from the blue chip will then easily passes through YAG:Ce^{3+} layer and gets to other layers. It can also be referred that the YRG structure increase the amount of light transmitted from the chips. This results in YRG having the highest spectral intensity while in the same emission spectrum as other structures.

As a result, it is possible to choose the YRG structure as an enhancement option for lighting devices that need to improve both color quality and light output. Beside other aspects, color uniformity is another deciding factor to the color of light that can be omitted. As of the solutions for better color uniformity, some used phosphor particles that enhance the scattering effect such as TiO_2, ZnO,... or applied the conformal coating method. The color quality can be be improved, yet lumen output would decline when the mentioned methods are implemented. Therefore, adding green (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb phosphor and red $LiAl_5O_8$:Fe^{3+} phosphor will enhance the chromatic performance with the support from green and red scattering properties. The back-scaterring effect that lowers light output is also lessen if remote phosphor structure were applied. Beside the mechanism of the structure, the component particular such as phosphor concentration is also important to enable WLEDs to the highest potential. The influence of phosphor concentration can be confirmed by Lambert-Beer law in (6). Figure 7 expresses the chromatic deviation in the structures, which shows that YRG is the structure with the lowest index regarding this indicator. The smaller the color deviation, the better color uniformity. This resulted from the scattering properties of the additional phosphor layers in YRG structure increase the scattering events in WLEDs and through that strengthen color uniformity. The down side of more scattering eventsis the reduction of light output. This small decline in light output can be compensated with the amount of emitted light increased as the back-scattering is managed. In conclusion, the YRG structure has the best performance in chromatic homogeneity and lumenoutput while Y structure is the oppsite due to color deviation and being a single-layer structure.

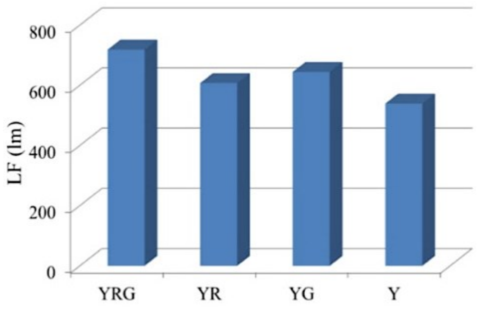

Figure 6. Luminous efficacy of phosphor configurations

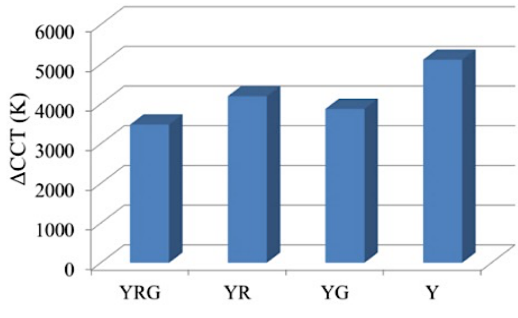

Figure 7. Corelated color temperature deviation (ΔCCT) of the remote phosphor configurations

4. CONCLUSION

The research aim for a practical solution to enhance optical properties by analyzing the lighting performance of Y, YG, YR and YRG structures at ACCT of 6600 K. Green (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb phosphor and red $LiAl_5O_8$:Fe^{3+} phosphor are used for the simulation processes. Aside from the experiemnts and theories, the the Mie theory and the Lambert-Beer law were also applied to verified the results. As observed from the results, green (Ce,Tb)$MgAl_{11}O_{19}$:Ce:Tb phosphor benefits the chromatic uniformity and lumen output with additional green particles, which is shown by the better values of mentioned in YG structure in comparision to YR structure. The red $LiAl_5O_8$:Fe^{3+} phosphor, on the other hand, improves CRI and CQS using red phosphor particles, which is verified by greater CRI and CQS in YR than YG. The YRG structure with two chromatic phosphor layers added in can effectively manage the balance of yellow, green and red which contributes to better color quality. Moreover, the reduction of backscattering effect in YRG induces a significant development in the luminous flux of this structure. Evidently, the highest luminous flux is also in the YRG structure. Based on the results of this study, producers can now choose a suitable structure to serve the purpose of enhancing the quality of WLEDs.

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