TELKOMNIKA, Vol.17, No.6, December 2019, pp.2931~2939
ISSN: 1693-6930, accredited First Grade by Kemenristekdikti, Decree No: 21/E/KPT/2018
DOI: 10.12928/TELKOMNIKA.v17i6.13093

The usage of dual-layer remote phosphor configurations in enhancing color quality and luminous flux of WLEDs

Thuc Minh Bui[1], Phan Xuan Le[2], Dinh Hoang Bach[3], Nguyen Doan Quoc Anh*[4]
[1]Faculty of Electrical and Electronics Engineering, Nha Trang University, Nha Trang City, Vietnam
[2]National Key Laboratory of Digital Control and System Engineering, Ho Chi Minh City, Vietnam
[3]Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[4]Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
*Corresponding author, e-mail: nguyendoanquocanh@tdtu.edu.vn

Abstract

Among conformal phosphor structure, in-cup phosphor structure, and remote phosphor structure, while in term of attaining the highest luminous flux, remote phosphor structure is the most ideal one, it seems to be that this structure results in the lowest-quality of color. Therefore, it is necessary in conducting experiments to surmount this disadvantage and make a possibility in enhancing the color quality of WLEDs with remote phosphor structure. In this research, with the ability of advancing the color rendering index (CRI) and color quality (CQS) for WLEDs, a dual-layer remote phosphor structure was considered as a suggestion. The experiments in this study used three kinds of WLEDs with the similar structures but different color temperatures varying at 5600 K, 7000 K, and 8500 K. The objectives of this paper is proposing a solution to obtain the highest color quality by placing a yellow-green emitting $SrBaSiO_4:Eu^{2+}$ phosphor layer or a red-emitting $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor layer on the $YAG:Ce^{3+}$ phosphor layer and then choosing the most appropriate value of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentration. The experimental results which are satisfied expectations of researchers indicated that $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ has enforced its role in managing to raise the CRI and CQS. Particularly, the greater concentration of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ leads to the higher the CRI and CQS, since the red light component in WLEDs increased. Besides, the quality of luminous flux is in a tight connection with the $SrBaSiO_4:Eu^{2+}$ phosphor layer. Whereas, according to the Mie scattering theory and the Lambert-Beer law, if the concentration of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ and $SrBaSiO_4:Eu^{2+}$ becomes redundant, the luminous flux and color quality will take a deep dive. Briefly, the results from this article has largely contributed to fabricating high-quality WLEDs.

***Keywords**: color rendering index, lambert-beer law, luminous efficacy, white LED*

1. Introduction

These days, the traditional light sources cannot meet the increasing and complicating demand for lighting, and become obsolete; thus, there is a need in getting the traditional light sources supplanted by other state-of-the-art ones. In an effort to fulfill this purpose, phosphor converted white light emitting diodes (pc-WLEDs), the fourth potential generation light source, was invented to become the superior in the illumination market and extend its application in different fields of our daily life such as landscape, street lighting, backlighting, etc [1-3]. However, the obstacles preventing the white LED from reaching its integrity are the limitations in light extraction efficiency and angular homogeneity of correlated color temperature. Hence, it is essential to eliminate these two problems to be able to expand the consumption market and make the best use of the advantages of white LEDs. Furthermore, one of the most optimum measures for the white light generation, so far, is the combination between the blue light from converse red phosphor and the yellow light from LED chip [4-7]. Although this idea is likely to be familiar, the importance of the structure of LEDs and the arrangement of phosphor layers in altering the luminous efficiency, especially the color rendering index, is undeniable. There are some suggested common phosphor coating methods in manufacturing LEDs such as dispensing coating and conformal coating [8-11]. Nevertheless, these common methods could not get the color quality reached the highest degree as the ability of the light conversion of

Received May 11, 2019; Revised July 2, 2019; Accepted July 18, 2019

phosphor material is reduced due to the yellow emitting phosphor directly contacting with the LED chip, leading to the growth in temperature at the junction point of the LED and phosphor layer. Therefore, to assure that the phosphor's performance is improved, and the phosphor is protected from damaging, the method is decreasing the degree of heat by setting up the phosphor away from the heat source (LED chip) [12-14]. If the phosphor is placed in an appropriate distance to the LED chips, we could limit the event of the backscattering and light circulation inside LED [15-17]. Thus, it could be concluded that this approach is an optimal solution to manage the temperature of LED, and improve the luminous efficiency as well as the LEDs' color quality. Nevertheless, the remote phosphor structure can only meet the requirements of regular lighting, which might be the reason why there is a need of producing the next generation of LED. For further advancement, the backscattering of phosphors to the chip must be minimized and the illumination efficiency must be magnified through some structures. Another study pointed out that it is possible to redirect the light from the LED chip to the surface of the LED and then minimize the loss because of the internal reflection inside the LED with an inverted cone lens encapsulant and a surrounding ring remote phosphor layer [18, 19]. Moreover, with a clear region in the perimeter area without coating phosphor on the surrounding surface, a patterned remote phosphor structure could attain high uniformity of angular-dependent correlated color temperature and chromatic stability [20, 21]. Furthermore, the correlated color temperature uniformity could be lifted to a higher degree in a far field pattern than a conventional one, when the patterned sapphire substrate is added to the remote phosphor. Hence, for achieving the better light output of LEDs, remote phosphor with dual layer package is proposed. Though, in previous mentioned studies, the color uniformity and the output luminous flux improvement of WLEDs with phosphorus remote structure was also focused, the experiments were still carried out with the single chip WLEDs and low values of color temperatures, leading to the limitations in fulfilling their objective. Besides, raising the optical parameters for WLEDs with higher color temperature is a complex issue. In addition, the preferences used to compare the performance of different kinds of dual-layer phosphor configurations have remained unavailable. Thus, the challenge raised for manufacturers is how to determine the most optimal method for the color quality or the output luminous flux enhancement of WLEDs.

While the first idea was aimed to the increase of the green light component in WLEDs by applying the $SrBaSiO_4:Eu^{2+}$ green phosphor layer in order to promote the photon emission, in the second idea, the application of the red phosphoric layer $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ served the purpose of getting the amount of red light component in WLEDs grown, from which CRI and CQS reach the upper level. Additionally, detailed descriptions of the chemical composition of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ as well as their effects on the optical properties of WLEDs are also included in the article. According to the results from the article, the increase in CRI and CQS could be assured by adding the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor layer. Nonetheless, as mentioned above, the concentration of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ should be controlled in an appropriate amount to avoid sharply declining the color quality or the output luminous flux sharply, when the concentration of green or red phosphors is lifted. As the yellow $YAG:Ce^{3+}$ phosphor layer is added the green or red phosphor layer, it is noticed that there are two unignorable differences. First, as the green or red light grows, the white light spectra increases, leading to the advance of color quality. Second, the direction of the concentration of additional phosphors determines the scattering and light transmission in WLEDs. Therefore, the suitable selection for the phosphor concentration plays a crucial role in maintaining the photosensitive performance of WLEDs.

2. Preparation

2.1. Preparation of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ Particles

Particles of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$, a type of yellow-green phosphor famous for its remarkable features including high quantum efficiency and stability at high temperature, have gained their popularity in this field. Furthermore, the application of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor is concentrated on very high-loading and long life-time fluorescent lamps.

Table 1 and Table 2 demonstrated the chemical composition of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$, considered as one of the elements greatly affecting the phosphor's optical properties. Hence, it is important to analyze each component to apply these phosphors in WLEDs production. At the peak wavelength of 2.36 eV, yellow-green light is emitted from $SrBaSiO_4:Eu^{2+}$; and the illumination efficiency of $SrBaSiO_4:Eu^{2+}$ is risen due to the contribution of Eu^{2+} ions. In contrast, $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ emits red light at diverse values of the peak wavelength including 684, 693, 697, 703, 723, 725, or 732 nm. Similar to Eu^{2+}, the presence of Sm^{2+} ion gets the absorption gone up at varied peak values of 395, 420, and 502 nm. Therefore, the effectiveness of the red phosphor $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$, or the optical is higher when the peak wavelength has more values.

Table 1. Composition of Yellow-Green Emitting $SrBaSiO_4:Eu^{2+}$ Phosphor

Ingredient	Mole (%)	By weight (g)	Molar mass (g/mol)	Mole (mol)	Ions	Mole (mol)	Mole (%)
$SrCO_3$	31.28	145	147.63	0.982	Sr^{2+}	0.982	0.088
$BaCO_3$	31.79	197	197.34	0.998	Ba^{2+}	0.998	0.090
SiO_2	33.40	63	60.08	1.049	Si^{4+}	1.049	0.094
Eu_2O_3	0.32	3.5	351.926	0.01	O^{2-}	8.068	0.726
NH_4Cl	3.22	5.4	53.49	0.101	Eu^{2+}	0.02	0.002

Table 2. Composition of Red-Emitting $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ Phosphor

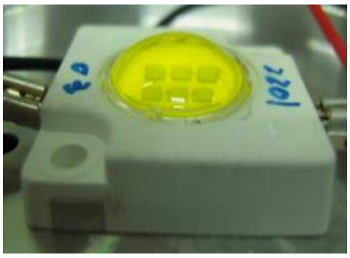
Ingredient	Mole (%)	By weight (g)	Molar mass (g/mol)	Mole (mol)	Ions	Mole (mol)	Mole (%)
$Sr(NO_3)_2$	10.09	126.98	211.63	0.6	Sr^{2+}	0.6	0.0241
SrF_2	5.43	40.58	125.62	0.32	F^-	0.646	0.0259
H_3BO_3	84.12	309.2	61.83	5	B^{3+}	5	0.203
Eu_2O_3	0.25	5.28	351.93	0.015	O^{2-}	18.665	0.748
Sm_2O_3	0.11	2.09	348.72	0.006	Eu^{2+}	0.03	0.0012
		$Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$			Sm^{2+}	0.012	0.00048

To be applied in the production process, these phosphors must have a spectrum compatible with blue light from the LED chip, which means there is a consistency of the absorption spectra of these phosphors and the spectrum of the blue chip. For instance, the appropriate range for $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ absorption spectrum to absorb the emitted light in different bands is from 250 nm to 502 nm due to the existence of both emitted blue light and converted yellow light from the yellow phosphor layer. Similarly, the range of absorption spectrum of $SrBaSiO_4:Eu^{2+}$ is wide, from 3.4 eV to 4.88 eV with over 70% absorption efficiency.

For the preparation of carrying out the optical simulation of the $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ components, the input parameters including phosphorus concentration, size of phosphor particles, excitation spectrum, spectral absorption, and emission spectra of phosphorus should be exactly set by conducting experiments. Among those parameters mentioned above, the concentration and the size of the phosphor are vital to get the best color and luminous flux of LED. In fact, the parameters of spectrum are constant. Based on the results of aforementioned researches, the phosphoric particles were set at fixed value of 14.5 μm in diameter. However, there was an adjustment in the concentrations of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphors to determine the optimum value.

2.2. Construction of Green-Yellow Dual-Layer Phosphor Configuration and Red-Yellow Dual-Layer Phosphor Configuration

Figure 1 (a) illustrates the actual WLEDs with 9 internal LED chips applied in this research. Each blue chip has the output value of 1.16W which reaches the peak at 453 nm. In Figure 1 (b), there is the LED profile specifications' details. For figuring out the optimal value of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentration, the remote phosphor model need to be constructed in the next step. Suggestions for the remote phosphor model in this study are two models of green-yellow dual-layer phosphor configuration (GYC) and red-yellow dual-layer phosphor configuration (RYC). In the GYC structure, there are two phosphor layers placed on the blue chips. The layer of $SrBaSiO_4:Eu^{2+}$ phosphor is above the yellow $YAG:Ce^{3+}$ phosphor layer, which is illustrated in Figure 1 (c). Demonstrated in Figure 1 (d) is the RYC structure, consisting of two phosphor layers covering the blue chips. $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor layer is put on the yellow YAG:Ce^{3+} phosphor layer. The application of GYC and RYC configurations aims at the enhancement of the color and the output luminous flux of WLEDs resulting from the rise in the scattering and composition of both green light and red light in WLEDs. However, the compatible calibration in the schema of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ is essential to carry out.



(a)

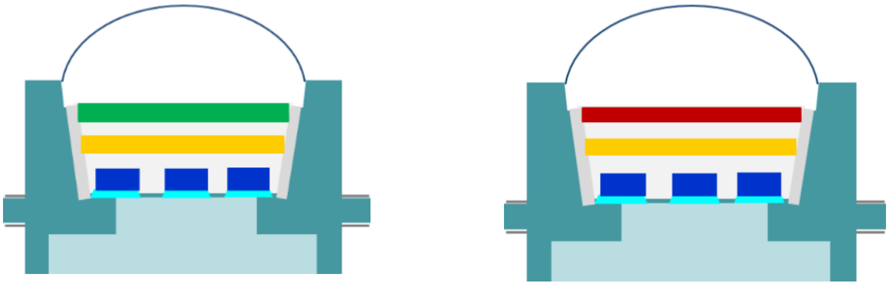
Lead frame: 4.7 mm Jentech Size-S

LED chip: V45H

Die attach: Sumitomo 1295SA

Gold Wire: 1.0 mil
Phosphor: ITC NYAG4_EL

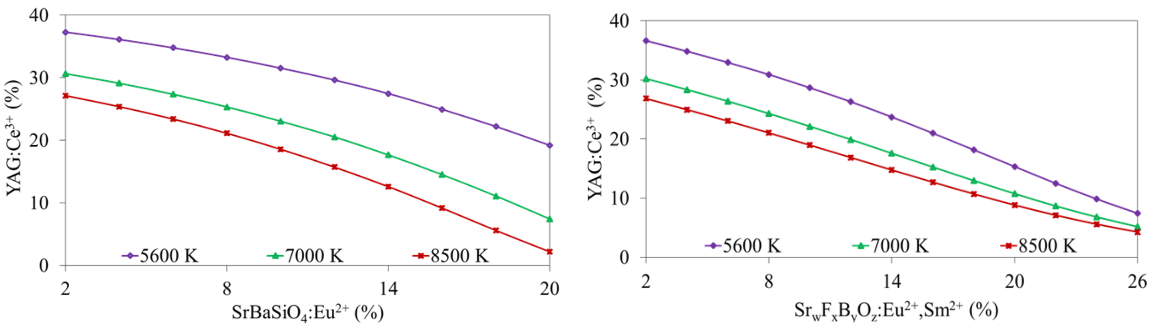
(b)



(c) (d)

Figure 1. Illustration of pcWLEDs: (a) the actual WLEDs and (b) its parameters; (c) illustration of GYC, and (d) RYC

As in Figure 2, the opposition in the change of the phosphor concentration between the green phosphor $SrBaSiO_4:Eu^{2+}$ and the red phosphor $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$, in accordance with the yellow phosphor YAG:Ce^{3+}, is described. This difference remains the average CCTs having effects on the scattering and absorption of two phosphor layers in WLEDs, resulting in unavoidable impacts on the color quality and luminous flux generated by WLEDs. Therefore, the factor deciding the color quality of WLEDs is the selection of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentrations. When raising the concentration of SrBaSiO4:Eu^{2+} and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ by 2-20% wt. and 2-26% wt., YAG:Ce^{3+} concentration declined to maintain the stability of the average CCTs. Similar to WLEDs with different color temperatures of 5600 K, 7000 K, and 8500 K, this phenomenon has the same way applying.



(a) (b)

Figure 2. The change of phosphor concentration of (a) GYC and (b) RYC for keeping the average CCTs

Figure 3 indicated that the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentration obviously influences the transmittance spectrum of WLEDs. If the WLEDs are expected to be produced with high color quality, their luminous flux should be allowed to be reduced in a small amount. In the two ranges 420-480 nm and 500-640 nm of light, a rise in the intensity is likely to appear with the concentration of $SrBaSiO_4:Eu^{2+}$ forming a proof of the intensification in the photon emission. Additionally, the increase in the blue-light scattering in WLED advances the degree of the scattering in the phosphor layer and in WLEDs, which benefits the color uniformity as a result. Therefore, this result pointed out the importance of $SrBaSiO_4:Eu^{2+}$ application. Besides, the increase in red light spectrum, from 648 nm to 738 nm with $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentration, can be easily realized. Yet, this change is insignificant, if the spectrum of two ranges 420-480 nm and 500-640 nm is not in an upward trend. Noticeably, the spectrum improvement of 420-480 nm lifts the blue-light scattering higher. If the color temperature is higher, the emission spectra becomes higher and leads to the better performance in color and luminous flux. Hence, this result proved the vital role of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$. As managing the color quality WLEDs has been facing many obstacles, but $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ has an outstanding ability in magnifying the color quality of WLEDs without concerning low color temperature (5600 K) or high color temperature (8500 K).

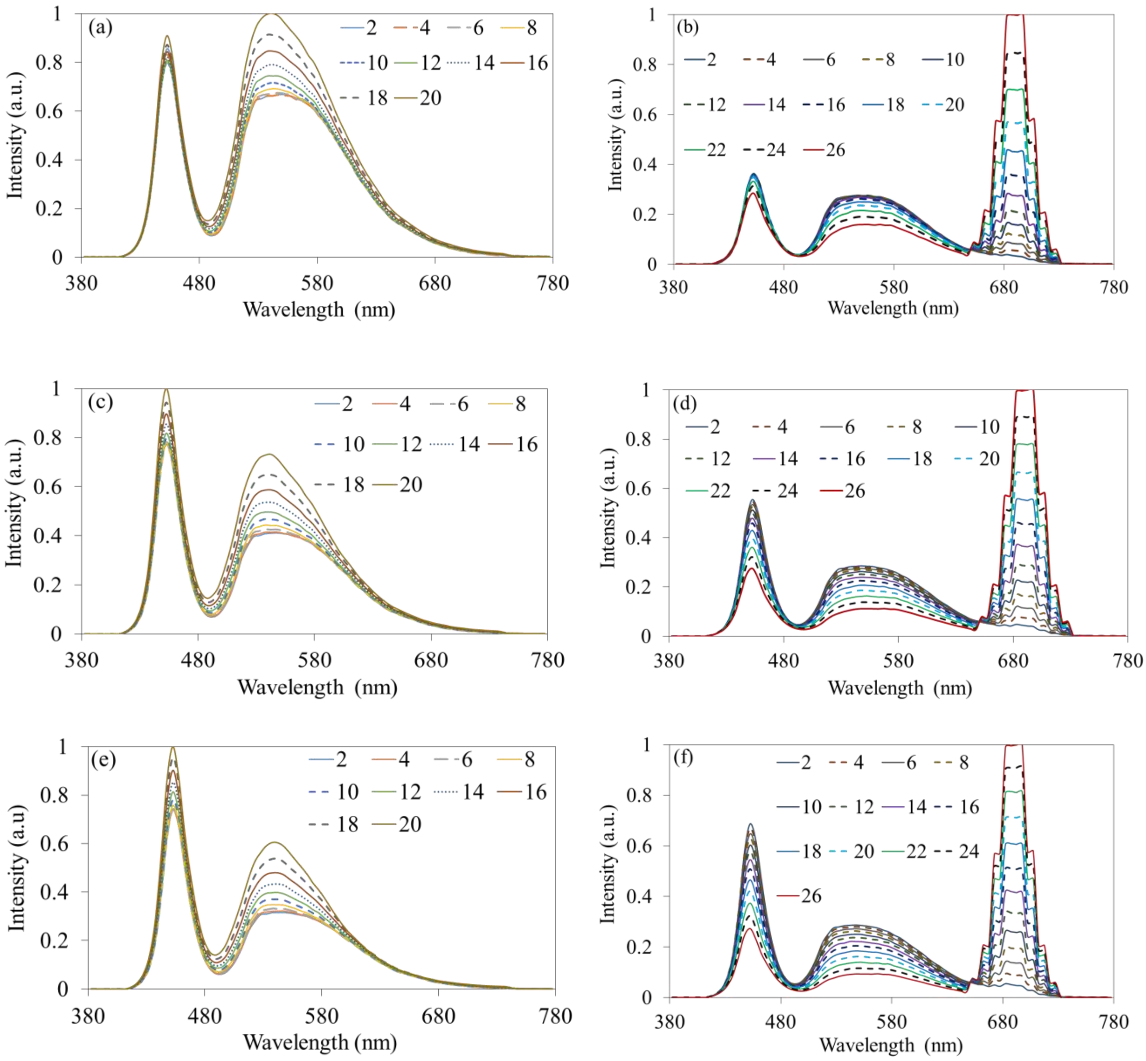
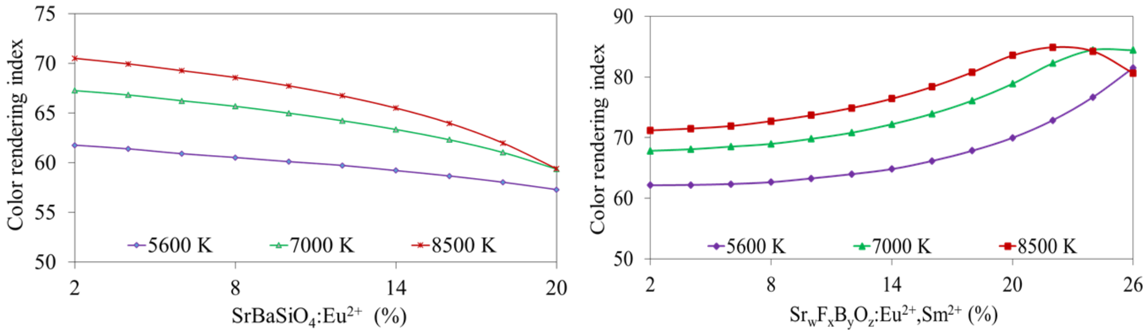


Figure 3. Emission spectra of GYCs and RYCs at the average CCTs of 5600 K, 7000 K and 8500 K, in turn are shown in (a,b), (c,d), (e,f) respectively

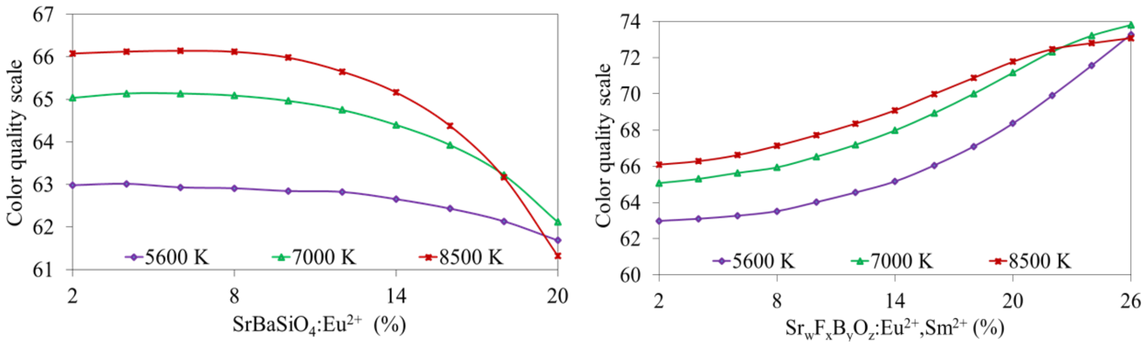
3. Computation and Discussion

In this study, to evaluate the degree of accurate colors of objects performed during the time lighting, the color rendering index is used. The imbalance among three main colors: blue, yellow, and green occurs as the green light component increase, leading to the influence on the color quality of WLEDs, and then reduce the accuracy in generated colors of WLEDs. As shown in Figure 4, the results indicated that the CRI declines when the $SrBaSiO_4:Eu^{2+}$ remote phosphor layer presents. Nonetheless, if compared to CQS, which is more crucial and faces more struggles in enhancing, this result of CRI is acceptable. According to Figure 5, CQS is still stable with the $SrBaSiO_4:Eu^{2+}$ concentration is less than 8%. Therefore, an ideal amount of concentration for $SrBaSiO_4:Eu^{2+}$ phosphor to be perfectly applied in WLEDs production is 8%, after the emission flux is considered.



(a) (b)

Figure 4. The color rendering index as a function of the concentration of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$: (a) GYC and (b) RYC



(a) (b)

Figure 5. The color quality scale as a function of the concentration of $SrBaSiO_4:Eu^{2+}$ and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$: (a) GYC and (b) RYC

From Figure 4, the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor concentration causes the colorimetric index to go up at all average CCTs. This phenomenon occurs due to the absorption process of red phosphor. When the blue light from the LED chip is absorbed by the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor, they are converted in to red lights by the red phosphor particles convert. Not only the blue light, but $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ particles also absorb the yellow light. However, the absorption of the blue light by the LED chip is stronger than the other because of the absorption properties of the material. Therefore, a higher color rendering index (CRI) can be achieved, when the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ is added and then gets the red light component in WLEDs risen. As the importance of the color rendering index in selecting WLED these days, it is obvious that the higher degree of the color rendering index results in the higher price of white light WLED. However, the production cost will be saved if the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor is applied in WLEDs fabrication.

In this way, the application of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ in WLEDs manufactures could be widen. However, to give the best evaluation of the color quality of WLEDs, it is not just based on the CRI, which means when a WLED has a good color quality, its color rendering index does not need to be high. Hence, a new parameter known as color quality scale (CQS) is mentioned as a new proposal in this article. CQS is a metric system defined by three factors: the color index, the viewer's preference, and the color coordinates. Due to using these three key factors, CQS has become a superior metric that can ascertain the overall color quality of WLEDs. In Figure 5, it is illustrated the CQS increases when there is the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ remote phosphor layer, especially, a strong growth in the CQS occurs when the concentration of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ rises.

It is undeniable that the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor can lift the white light quality of WLEDs to higher degree with dual-layer phosphor structures, which seems to reach the edge of the objective of the research, color quality enhancement. On the other hand, the drawback in the output luminous flux of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ should not be ignored. In this section, the mathematical model of the transmitted blue light and converted yellow light in the double-layer phosphor structure will be expressed and demonstrated, based on which it is able to get the LED efficiency greatly heighten. The expressions of the transmitted blue light and converted yellow light for single layer remote phosphor package with the phosphor layer thickness of 2*h* are shown as below:

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

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

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

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

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

In these expressions, *h* is the thickness of each phosphor layer. The subscripts “1” and “2” illustrate the single layer and double-layer remote phosphor package. β indicates the conversion coefficient for blue light converting to yellow light, and γ presents the reflection coefficient of the yellow light. PB_0 expresses the light intensities of blue light (*PB*) and yellow light (*PY*) from blue LED. α_B; α_Y describe the fractions of the energy loss of blue and yellow lights during their propagation in the phosphor layer respectively.

In comparison with the single layer structure, the double-layer phosphor structure can significantly improve the lighting efficiency of pc-LEDs:

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

while the Mie-theory [22, 23] is applied in analyzing the scattering of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor particle, and calculating the scattering cross section C_{sca} for spherical particles as the expression below, the Lambert-Beer law [24, 25] is used to computed the transmitted light power:

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

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

Obviously, from (5), the dual-layer remote phosphor can generate the better light output of WLEDs than the single-layer phosphor. Hence, this article gives an explicit piece of evidence about the output effectiveness of the dual-layer remote phosphor layer. Besides, the attaining emission strongly rose as the increase from 2% wt. to 20% wt in the concentration of

$SrBaSiO_4:Eu^{2+}$ appeared, as illustrated in Figure 5. Whereas, the concentration of the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor layer influenced the dual-layer remote phosphor door. Especially, based on the Lambert-Beer law, the attenuation coefficient μ_{ext} is in proportion to the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentration except the ratio of light to energy. Thus, when firmly attaching the thickness of both phosphor layers of WLEDs to a specific value, the increase in $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentration can decrease the photon emission.

Figure 6 presented a trend of decline in luminous flux at overall three average CCTs with the presence of the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentration. It can be easily realized that when the concentration of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ is lifted up to 26%, the luminous flux exposed in a large decrease. Nevertheless, if the benefits of the $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ phosphor layer including CRI and CQS improvement, along with higher flux from the dual-layer remote phosphor compared to the single-layer phosphor layer (without the red phosphor layer) are taken into consideration, this downward trend is absolutely acceptable. The left issue is the appropriate amount of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ concentration which depends on the intention of manufacturers when produce this WELDs in a large quantity.

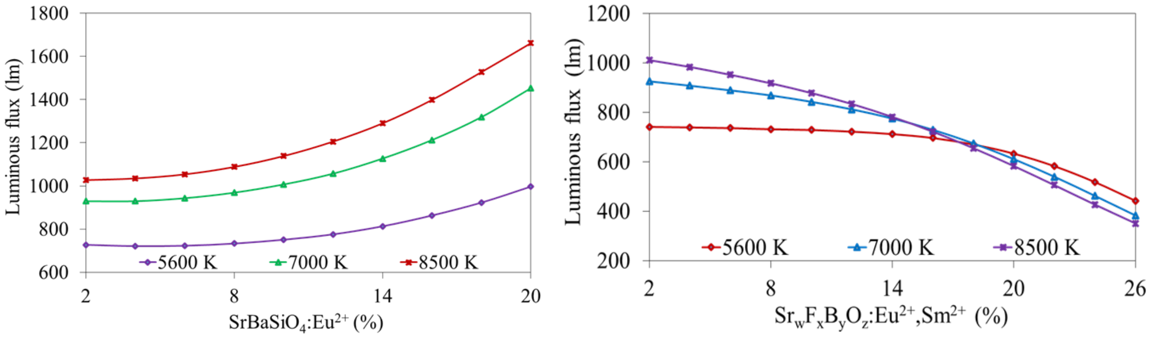


Figure 6. The luminous flux as a function of the concentration of SrBaSiO4:Eu2+ and SrwFxByOz:Eu2+,Sm2+: (a) GYC; (b) RYC

4. Conclusion

In brief, this research paper give a detailed demonstration on how $SrBaSiO_4:Eu^{2+}$ phosphor and $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ impact CRI, CQS, and luminous flux of dual-layer phosphor structures. By applying the Mie's scattering theory and the Lambert-Beer law, the article has consolidated the selection of $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ in advancing the color quality, while choosing $SrBaSiO_4:Eu^{2+}$ is consider as an approach in innovating WLEDs, which is applied for both low color temperature of 5600 K and high color temperatures above 8500 K WLEDs. Therefore, the outcomes from this study have reach the purpose of the improvement in the color quality of white light, which is considered as a complex challenge to the remote-phosphor structure. Yet, the drawback related to the emission of the flux still exits, which can be described that if the $SrBaSiO_4:Eu^{2+}$ or $Sr_wF_xB_yO_z:Eu^{2+},Sm^{2+}$ rapidly increase, the color quality or luminous flux will show a sharp decline. Thus, it is extremely vital to decide an appropriate concentration. Based on the goals that manufacturers desire to achieve, they could refer to the information provided in this paper to make the best decision, so that better quality WLEDs can be produced.

Acknowledgements

This research was supported by National Key Labrolatory of Digital Control and System Engineering (DCSELAB), HCMUT, VNU-HCM.

References

[1] Li CN, Rao HB, Zhang W, Zhou CY, Zhang Q, Zhang K. Self-Adaptive Conformal–Remote Phosphor Coating of Phosphor-Converted White Light Emitting Diodes. *Journal of Display Technology*. 2016; 12(9): 946-950.

[2] NDQ, Le PX, Lee HY. Selection of a Remote Phosphor Configuration to Enhance the Color Quality of White LEDs. *Current Optics and Photonics*. 2019; 3(1): 78-85.
[3] Li ZT, Wang HY, Yu BH, Ding XR, Tang Y. High-efficiency LED COB device combined diced V-shaped pattern and remote phosphor. *Chinese Optics Letters*. 2017; 15(4).
[4] Tin TP, Nhan NHK, Minh THQ, Lee HY. Red-emitting α-$SrO{\cdot}3B_2O_3$:Sm^{2+} Phosphor for WLED Lamps: Novel Lighting Properties with Two-layer Remote Phosphor Package. *Current Optics and Photonics.* 2017; 1(4): 389-395.
[5] Nhan NHK, Minh THQ, Tan NN, Voznak M. Bi-layers Red-emitting $Sr_2Si_5N_8$:Eu^{2+} Phosphor and Yellow-emitting YAG:Ce Phosphor: A New Approach for Improving the Color Rendering Index of the Remote Phosphor Packaging WLEDs. *Current Optics and Photonics.* 2017; 1(6): 613-617.
[6] Ying SP, Shen JY. Concentric ring phosphor geometry on the luminous efficiency of white-light-emitting diodes with excellent color rendering property. *Optics Letters*. 2016: 41(9): 1989-1992.
[7] Chiang CH, Tsai HY, Zhan TS, Lin HY, Fang YC, Chu SY. Effects of phosphor distribution and step-index remote configuration on the performance of white light-emitting diodes. *Optics Letters*. 2015; 40(12): 2830-2833.
[8] Yu SD, Li ZT, Liang GW, Tang Y, Yu BH, Chen KH. Angular color uniformity enhancement of white light-emitting diodes by remote micro-patterned phosphor film. *Photonics Research*. 2016; 4(4): 140-145.
[9] Jeon SW, Kim SH, Choi JN, Jang IS, Song YH, Kim WH, Kim JP. Optical design of dental light using a remote phosphor light-emitting diode package for improving illumination uniformity. *Applied Optics*. 2018; 57(21): 5998-6003.
[10] Xie B, Chen W, Hao JN, Wu D, Yu XJ, Chen YH, Hu R, Wang K, Luo XB. Structural optimization for remote white light-emitting diodes with quantum dots and phosphor: packaging sequence matters. *Optics Express*. 2016; 24(26): A1560-A1570.
[11] Li JS, Li ZT, Liang GW, Yu SD, Tang Y, Ding XR. Color uniformity enhancement for COB WLEDs using a remote phosphor film with two freeform surfaces. *Optics Express*. 2016; 24(21): 23685-23696.
[12] Shih BJ, Chiou SC, Hsieh YH, Sun CC, Yang TH, Chen SY, Chung TY. Study of temperature distributions in pc-WLEDs with different phosphor packages. *Optics Express*. 2015; 23(26): 33861-33869.
[13] Mirhosseini R, Schubert MF, Chhajed SC, Cho J, Kim JK, Schubert EF. Improved color rendering and luminous efficacy in phosphor-converted white light-emitting diodes by use of dual-blue emitting active regions. *Optics Express*. 2009; 17(13): 10806-10813.
[14] Nizamoglu S, Erdem T, Sun XW, Demir HV. Warm-white light-emitting diodes integrated with colloidal quantum dots for high luminous efficacy and color rendering: reply to comment. *Optics Letters*. 2011; 36(15): 2852-2852.
[15] Thornton WA. Luminosity and Color-Rendering Capability of White Light. *Journal of the Optical Society of America*. 1971; 61(9): 1155-1163.
[16] Sahu IP, Bisen DP, Tamrakar RK. Dysprosium-Doped Strontium Magnesium Silicate White Light Emitting Phosphor Prepared by Solid State Reaction Method. *Journal of Display Technology*. 2016; 12(11): 1478-1487.
[17] Singh VK, Tripathi S, Mishra MK, Tiwari R, Dubey V, Tiwari N. Optical Studies of Erbium and Ytterbium Doped $Gd_2Zr_2O_7$ Phosphor for Display and Optical Communication Applications. *Journal of Display Technology*. 2016; 12(10): 1224-1228.
[18] Chen LY, Chang JK, Wu YR, Cheng WC, Chen JH, Tsai CC, Cheng WH. Optical Model for Novel Glass-Based Phosphor-Converted White Light-Emitting Diodes. *Journal of Display Technology*. 2013; 9(6): 441-446.
[19] Park HK, Oh JH, Do YR. Toward scatter-free phosphors in white phosphor-converted light-emitting diodes. *Optics Express*. 2012; 20(9) 10218-10228.
[20] Oh JH, Kang HJ, Ko MJ, Do YR. Analysis of wide color gamut of green/red bilayered freestanding phosphor film-capped white LEDs for LCD backlight. *Optics Express*. 2015; 23(15): A791-A804.
[21] Ying SP, Fu HK, Tu HZ. Curved remote phosphor structure for phosphor-converted white LEDs. *Applied Optics*. 2014; 53(29): H160-H164.
[22] Wang MT, Huang JM. Accurate control of chromaticity and spectra by feedback phosphor-coating. *Optics Express*. 2015; 23(9): 11576-11585.
[23] Kim SN, Iqbal F, Kim HS. Relationship between phosphor properties and chromaticity of phosphor-in-glass. *Applied Optics*. 2017; 56(34): 9477-9483.
[24] Garlick GFJ, Gibson AF. The Luminescence of Photo-Conducting Phosphors. *Journal of the Optical Society of America*. 1949; 39(11): 935-941.
[25] Ying SP, Shiu AY. Investigation of remote-phosphor white light-emitting diodes with improved scattered photon extraction structure. *Applied Optics*. 2015; 54(28): E30-E34.