

# SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> phosphor: a novel application for improving the luminous flux and color quality of multi-chip white LED lamps

Nguyen Thi Phuong Loan<sup>1</sup>, Nguyen Doan Quoc Anh<sup>2</sup>

<sup>1</sup>Faculty of Fundamental 2, Posts and Telecommunications Institute of Technology, Vietnam

<sup>2</sup>Power System Optimization Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Vietnam

## Article Info

### Article history:

Received Sep 11, 2019

Revised Apr 22, 2020

Accepted May 5, 2020

### Keywords:

Color quality scale

Luminous flux

Mie-scattering theory

SrBaSiO<sub>4</sub>:Eu<sup>2+</sup>

WLEDs

## ABSTRACT

This paper described in detail the chromatic homogeneity and luminous flux influences in producing better quality white LED devices with various phosphor layers (MCW-LEDs). The method is to let Eu<sup>2+</sup>-activated strontium–barium silicate (SrBaSiO<sub>4</sub>:Eu<sup>2+</sup>) mixed with their phosphor compounding, which results in notable impact on lighting performance. The increase in concentration of yellow-green-emitting SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> phosphor also promotes the color performance and lumen output of WLED devices at high correlated color temperature around 8500K. This is the first time this approach is applied and it results can be utilized for better understanding of optical properties interaction with phosphor materials. Although SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> receives many positive responses, we still need to limit its concentration for high SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> concentration is detrimental to CQS. The appropriate choice of concentration and size of SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> is the principal factor to decide the performance of MCW-LEDs.

Copyright © 2020 Institute of Advanced Engineering and Science.  
All rights reserved.

## Corresponding Author:

Nguyen Doan Quoc Anh,

Power System Optimization Research Group,

Faculty of Electrical and Electronics Engineering,

Ton Duc Thang University,

No. 19 Nguyen Huu Tho Street, Tan Phong Ward, District 7, Ho Chi Minh City, Vietnam.

Email: nguyendoanquocanh@tdtu.edu.vn

## 1. INTRODUCTION

Recently, perfecting the optical properties of WLED, especially the luminous efficacy and color-related attributes, is a leading research goal of many scientists, which has been mentioned in previous papers [1-5]. After many experiments, Anh and his colleagues discover the mixture of YAG:Ce<sup>3+</sup> phosphor compounding with SiO<sub>2</sub> particles could significantly increase the lighting efficiency of white LED lighting devices [6-8]. In addition, the combination of yellow YAG:Ce<sup>3+</sup> phosphor with the silicone substance could support the blue light and yellow light extraction [9-12] and also generate the white light. This process includes two stages: disintegrating in phosphor compounds and moving through phosphor particles, in which the YAG:Ce<sup>3+</sup> phosphor layer will metabolize the blue light and simultaneously make it become weaker [13-16]. However, the converted yellow light tends to be more intense after every scattering, which makes the normal extracted light from the WLED to be more blue, while if it is placed near the LED exterior, the color tends to be more yellow [17-19]. Won was in collaboration with his partner to prove the marked effect of phosphor configuration on the lighting efficiency of LED devices with great color quality scale (CQS), where blue LEDs and multiple phosphor materials such as green (Ba,Sr)<sub>2</sub>SiO<sub>4</sub>:Eu<sup>2+</sup> and red CaAlSiN<sub>3</sub>:Eu<sup>2+</sup> were applied in various phosphor structures to achieve optimal efficiency [20]. In contrast,

Oh's group proposed the multiple phosphor LED with three primary colors green, yellow, and red, which focus on enabling the luminous flux and color consistency to reach the most satisfactory result [21]. Zhang's team used multi-chromatic materials for better quality of CRI in LED products [22]. The improvement of CRI and optical output is of interest to many researchers, but the increase in color uniformity seems to be ignored. Furthermore, their research subjects is solely white LED with one chip, which gives out low CRI and therefore not really applicable to modern lighting applications that require multiple chips for lighting devices with high CCTs.

Understanding the needs for an advanced study in optical properties enhancement and more relevant results to the current WLED structures, this research present experiments in which the chromatic phosphor is employed in a multi-chip LED configuration. Based on previous studies that targeted at the optical properties such as lumen output, CRI, and chromatic quality, we introduce an innovative research method that exploits the advantageous findings while adding in new aspects for research. For example, the application of red phosphor  $\text{Mg}_8\text{Ge}_2\text{O}_{11}\text{F}_2:\text{Mn}^{4+}$  in the dual-layer WLED at 6600 K CCT is confirmed to optimize the lumen output and CRI. On the other hand, the remote phosphor configuration is proven to be the optimal set up for WLED among the three configurations including the in-cup phosphor and conformal phosphor after the achieved lumen output of this configuration is demonstrated as better than others [23-25]. However, there are currently a lack of diversity in the applicable types of phosphor for WLED. Therefore, we conducted experiments on a new phosphor, known as the yellow-green phosphor  $\text{SrBaSiO}_4:\text{Eu}^{2+}$ , on WLEDs with three different phosphor structures respectively. The approach this research suggests allow comparison between performances of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  in each phosphor configuration, which assists the identification of the best combination. The yellow-green  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  phosphor plays a supporting role for chromatic homogeneity and luminous efficacy so that the greatest efficiency could be attained from the phosphor materials in MCW-LEDs during the scattering process. The participation of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  particles will decide lighting quality color uniformity. Regarding the remote phosphor structure, there are the remote structure with two flat phosphor layers (FDRP) and the remote structure with two curved phosphor layers (CDRP). However, a preceding study claims that FDRP is the better choice as CDRP yields less lumen while having a more complex fabricating procedure, therefore, the dual-remote WLED in this research is simulated with FDRP arrangement [26-28]. This research has 3 phases: (1) Simulating the MCW-LEDs prototype; (2) Applying  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  as a phosphor material for the MCW-LEDs; (3) Studying the influences of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  on the optical properties, including the emission spectra and the scattering coefficient. In sum, mixing  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  and  $\text{YAG}:\text{Ce}^{3+}$  phosphors together is considered as an optimal method to maximize quality and lighting efficiency. The conclusions in this manuscript are useful references for luminous flux and chromatic performance development while also effective in supporting the manufacturers in choosing the suitable configuration for quality WLEDs production.

## 2. PREPARATION AND SIMULATION

### 2.1. Preparation of yellow-green $\text{SrBaSiO}_4:\text{Eu}^{2+}$ phosphor

Yellow-green  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  phosphor particles contain many superb characteristics, for example, great quantum yield and consistency at high temperature with an emission peak up to 2.36 eV, which makes it become more popular recently [29]. The particle sizes and concentration directly affect the luminescence properties of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  phosphor. The composition including  $\text{SrCO}_3$ ,  $\text{BaCO}_3$ ,  $\text{SiO}_2$ ,  $\text{Eu}_2\text{O}_3$ ,  $\text{NH}_4\text{Cl}$ , and  $\text{Eu}^{2+}$  ion are used as raw materials as shown in Table 1. Some heavy duty and long lifetime fluorescent lights prefer to use  $\text{SrBaSiO}_4:\text{Eu}^{2+}$ . Therefore, it turns into the most well-known commercialized oxide material in the lighting market. The fabrication process of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  is described specifically as follows:

Firstly, the materials are soaked in water to be dissolved before being crushed into small particles. Then they will be pulverized as soon as being dried in the air. Secondly, the powder will be heated in a closed quartz tube with CO at 1100°C for one hour and crushed into powder by dry grinding. Then 5.4 g  $\text{NH}_4\text{Cl}$  is added and mixed with this compound by dry grinding. Next, they will be reheated in the capped quartz tubes with CO at 1100°C for one hour and will be pulverized. Finally, the materials are washed in water several times (pH ranged from 10 to 12) and dried afterward.

Table 1. Composition of yellow-green-emitting  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  phosphor

Ingredient	Mole (%)	By weight (g)	Molar mass (g/mol)	Mole(mol)	Ions	Mole (mol)	Mole (%)
$\text{SrCO}_3$	31.28	145	147.63	0.982	$\text{Sr}^{2+}$	0.982	0.088
$\text{BaCO}_3$	31.79	197	197.34	0.998	$\text{Ba}^{2+}$	0.998	0.090
$\text{SiO}_2$	33.40	63	60.08	1.049	$\text{Si}^{4+}$	1.049	0.094
$\text{Eu}_2\text{O}_3$	0.32	3.5	351.926	0.01	$\text{O}^{2-}$	8.068	0.726
$\text{NH}_4\text{Cl}$	3.22	5.4	53.49	0.101	$\text{Eu}^{2+}$	0.02	0.002

## 2.2. Construction of MC-WLEDs

Based on the LightTools 8.5.0 software and Monte Carlo method [30-32], the prototype simulation of MCW-LEDs is conducted through two main periods with a flat silicone layer. Setting up and manufacturing the framework and lighting characteristics of MCW-LED at first, then the influences of phosphor compounding with different  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  concentration is analyzed based on the performance of MCW-LED with different phosphor geometries. The realistic simulated product is present in Figure 1(a) with technical measurements can be seen from Figure 1(b). Among them, the two types of compounding which have average CCT of 8500 K, conformal and in-cup phosphor, are picked to analyze. A distinct description for MCW-LEDs with conformal phosphor structure, in-cup structure, and remote structure with the average CCT of 8500 K was shown in Figure 1(c), (d), and (e) respectively. The components of the MCW-LED is an  $8 \times 2.07 \times 9.85$  mm at bottom, height, and surface reflector, 0.08 mm phosphor layer in phosphor compound, and 9 LED chips. Each chip is  $1.14 \text{ mm}^2$  in acreage and 0.15 mm in height with 1.16 W energy emission for each individual at 453 nm maximum wavelength connected to the base of the structure.

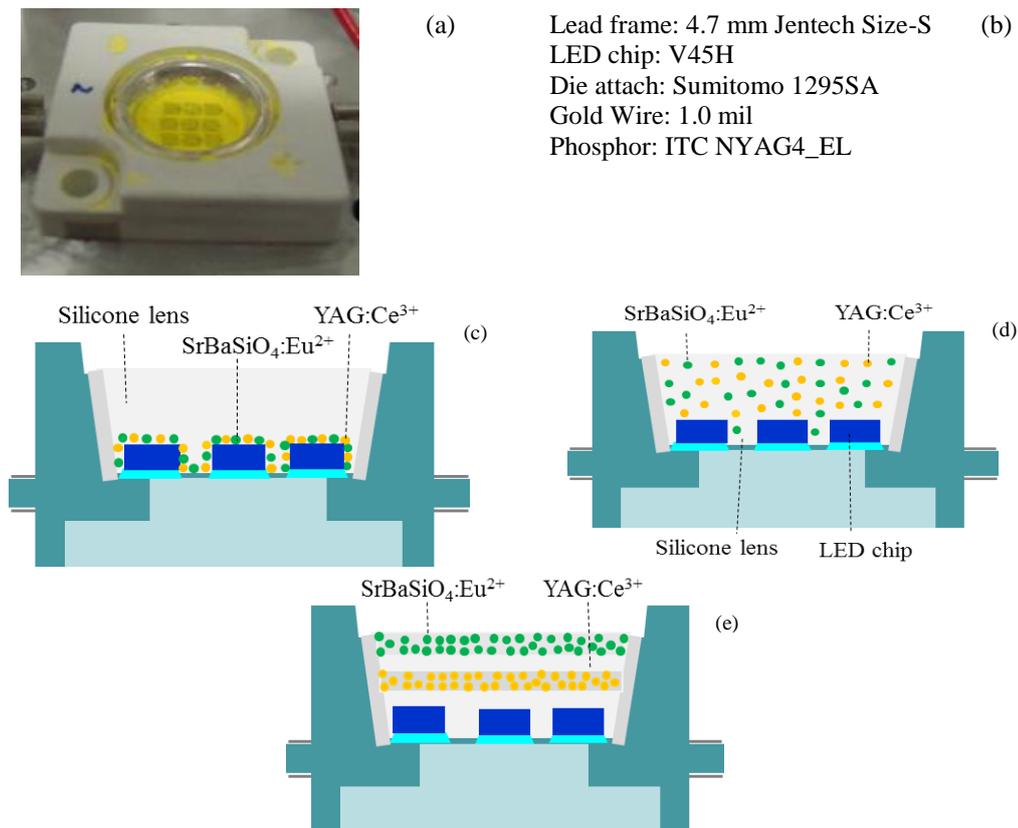


Figure 1. Illustration of phosphor-converted MCW-LEDs as doping  $\text{SrBaSiO}_4:\text{Eu}^{2+}$ : (a) the actual MCW-LEDs and (b) its parameters; (c) conformal phosphor geometry (CPG); (d) in-cup phosphor geometry (IPG); and (e) remote phosphor geometry (RPG)

As can be seen from Figure 1(c), the chips are covered with phosphor particles diffused by conformal coating. Conversely, separate methods are used for the structure with in-cup phosphor and for mixture with silicone lens. The scattering analysis of these two structures was carried out based on Mie-theory. The measurement for particles in this research is  $14.5 \mu\text{m}$  in size, similar to the real parameter. The phosphor composite is a combination of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$ ,  $\text{YAG}:\text{Ce}^{3+}$ , and the silicone gel with the same sizes as the real parameters and own the refractive indexes respectively of 1.85, 1.83, and 1.52. Once the refractive index and diameter of phosphor particles are set, we can study the emission spectra of research subjects. Figure 2 (top) described the emission spectra of the conformal structure WLED at different  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  concentration fluctuating from 0% toward 24%. Figure 2 (bottom) expresses in details the emission spectra of in-cup structure WLED with different ranges of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  concentration which can reach 1.4%. According to this chart, the lighting efficiency of MCW-LEDs will improve after  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  phosphor are added to the structure.

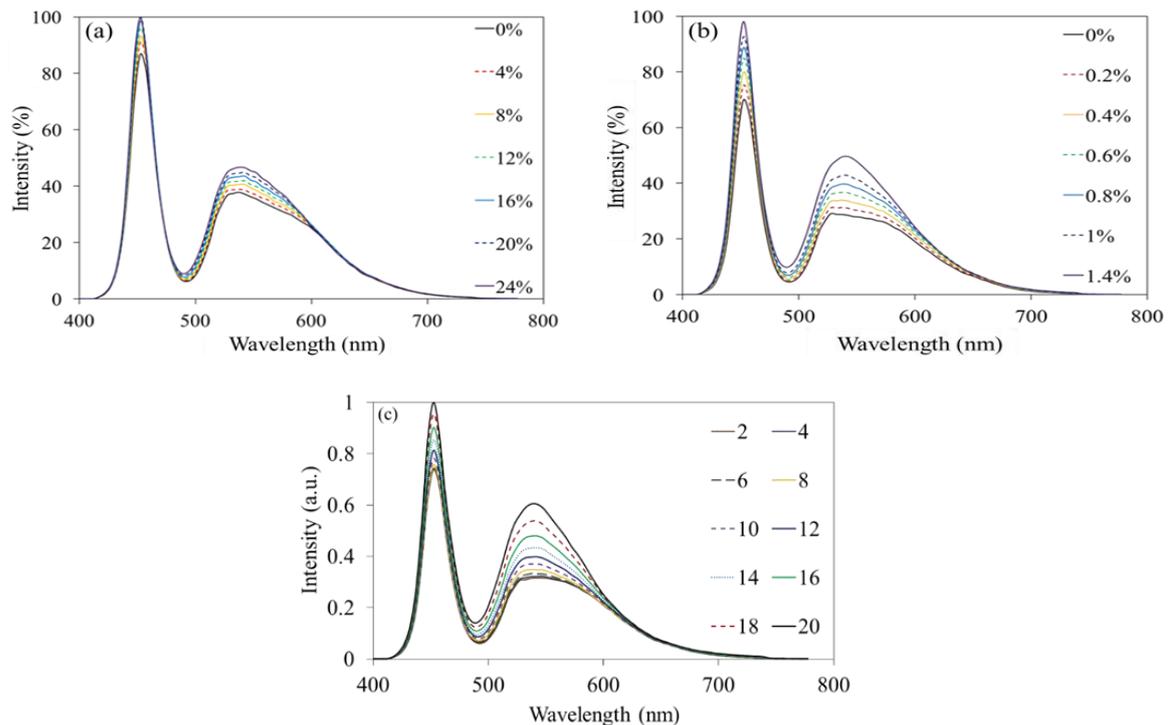


Figure 2. Emission spectra of multiple phosphors: (a) CPG; (b) IPG; and (c) RPG

### 3. COMPUTATION AND DISCUSSION

Based on the Mie theory [23-35], the scattering coefficient  $\mu_{sca}$  are computed to verify the optical properties of phosphor compounding. The relationship among the scattering coefficient (SC), the wavelength, and diameter of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  particles is expressed in the formula below:

$$\mu_{sca}(\lambda) = \frac{c}{\bar{m}} \bar{C}_{sca}(\lambda) \quad (1)$$

$$\bar{C}_{sca}(\lambda) = \frac{\int C_{sca,D}(\lambda) f(D) dD}{\int f(D) dD} \quad (2)$$

$$\bar{m} = \frac{\int m_i(D) f(D) dD}{\int f(D) dD} \quad (3)$$

$$C_{sca}(\lambda) = \frac{P_{sca}(\lambda)}{I_{inc}(\lambda)} \quad (4)$$

where,  $f(D)$  is the function of diameter distribution,  $c$  is the distribution density of phosphor ( $\text{g}/\text{cm}^3$ ),  $C_{sca,D}$  is the scattering cross-section of the phosphor having particle diameter  $D$ . While  $\bar{C}_{sca}(\lambda)$  and  $\bar{m}$  are the scattering cross-section and the particle mass of the phosphor integrated over  $f(D)$ , respectively.  $P_{sca}(\lambda)$  and  $I_{inc}(\lambda)$  are the scattered power by phosphor particles and the irradiance intensity in turn.

When  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  phosphor involves in the scattering, the scattering coefficient (SC) of the phosphor layer is indicated in Figure 3. Concentrations and other agents of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  will be the catalyst that makes SC of phosphorus mixture significantly change. This also verifies that previous concentrations and stimulation of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  affect the color quality of both CPG and IPG structures. When  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  concentration increases, SC also tends to develop regardless of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  particle size. With a size of about  $1 \mu\text{m}$ , SC can achieve optimum value and making color uniformity better regardless of the larger sizes. Therefore, if the target is CQS,  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  size can be approximately  $1 \mu\text{m}$ .

When it is approximately 7  $\mu\text{m}$ , the SC value of phosphorus is more stable regardless of the increase in  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  concentration, which brings color quality (CQS) of LED lights a lot of benefits. As a result, if the target is CQS, size less than 7 m can be chosen. Apparently, the SC value depends on the amount of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  particles and also their diameter, which is why  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  can be used to increase luminous efficiency and color uniformity of the LEDs. The appearance of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  is one of the factors affecting the color deviation result of MCW-LED as illustrated in Figure 4.

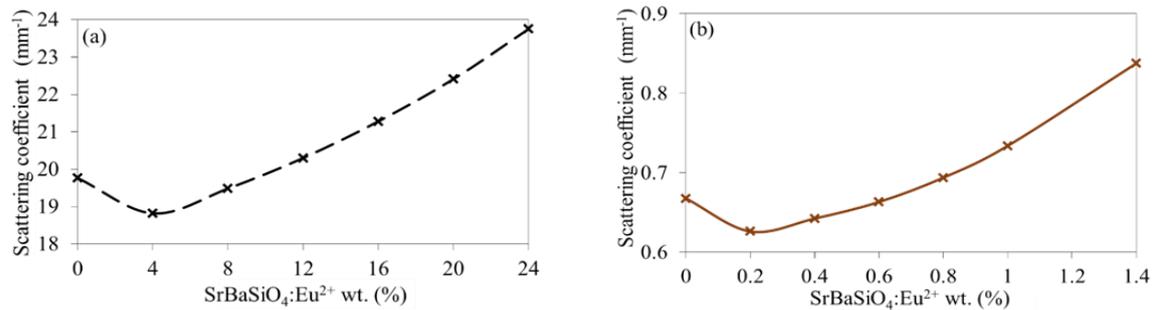


Figure 3. Scattering coefficients of phosphorus compounding at 453 nm as a function of the concentration and size of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$ : (a) CPG; (b) IPG

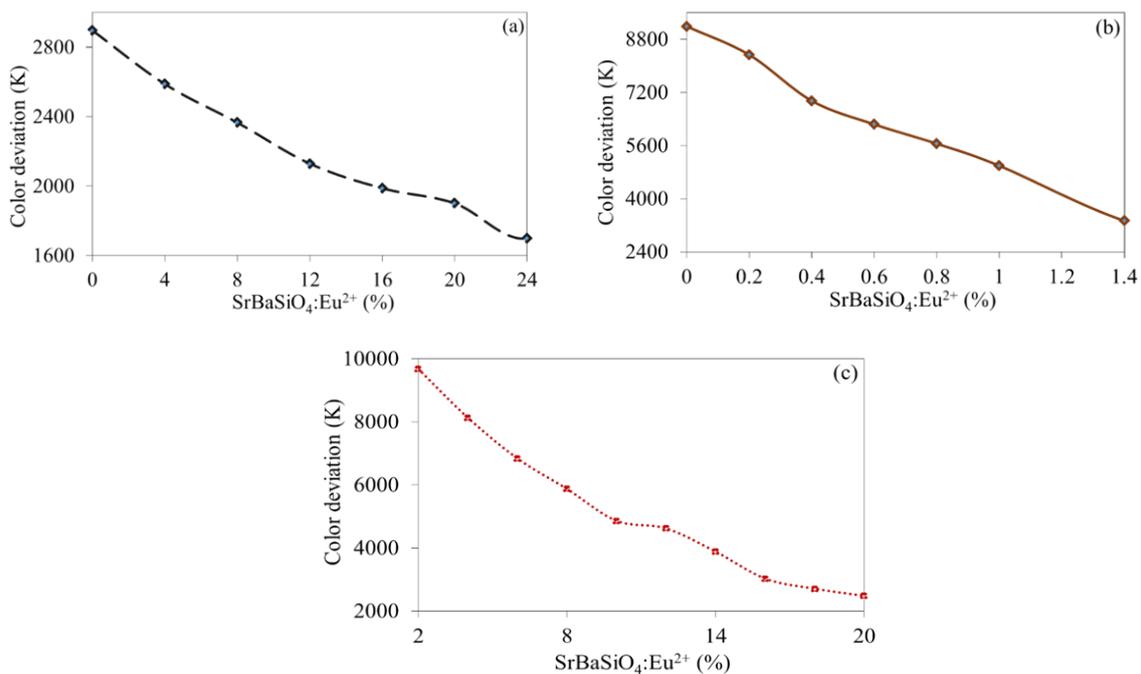


Figure 4. The CCT peak-valley deviation as a function of the concentration and size of  $\text{SrBaSiO}_4:\text{Eu}^{2+}$ : (a) CPG; (b) IPG; and (c) RPG

The CCT peak deviation decreases significantly when  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  is involved and keep going as the phosphor concentration increases. That means the spatial distribution of MCW-LED with  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  is much better than when the  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  is absence. There must be a balance between performance factors and optimization issues because if we only focus on optimizing one element, optical systems can be weak in other aspects. In addition, the greatest CQS and the luminous efficiency of white LED packages cannot be achieved at the same time. The solution is that the spectrum and wide source efficiency must be maximized in monochromatic radiation of 555 nm wavelength to better CRI. Therefore, the remaining optical properties that need optimization are CQS, luminous flux, and CCT P-V deviation values. Below are the Figure 5 that illustrates the luminous efficacy of WLED with  $\text{SrBaSiO}_4:\text{Eu}^{2+}$  and Figure 6 that shows

the color quality scale (CQS) in WLED with SrBaSiO<sub>4</sub>:Eu<sup>2+</sup>. It can be found from the simulation results these figures that the luminous yield grows along with SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> concentration. However, if SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> concentration continues to grow higher, the luminous flux will still follow, even though CQS will decrease. Therefore, for WLEDs that focus on the CQS values, it is advisable to limit the phosphor concentration under permitted level to prevent damaging CQS. Moreover, SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> concentration develops backward but not significantly, it will contribute to better CCT stability and greater luminous efficiency.

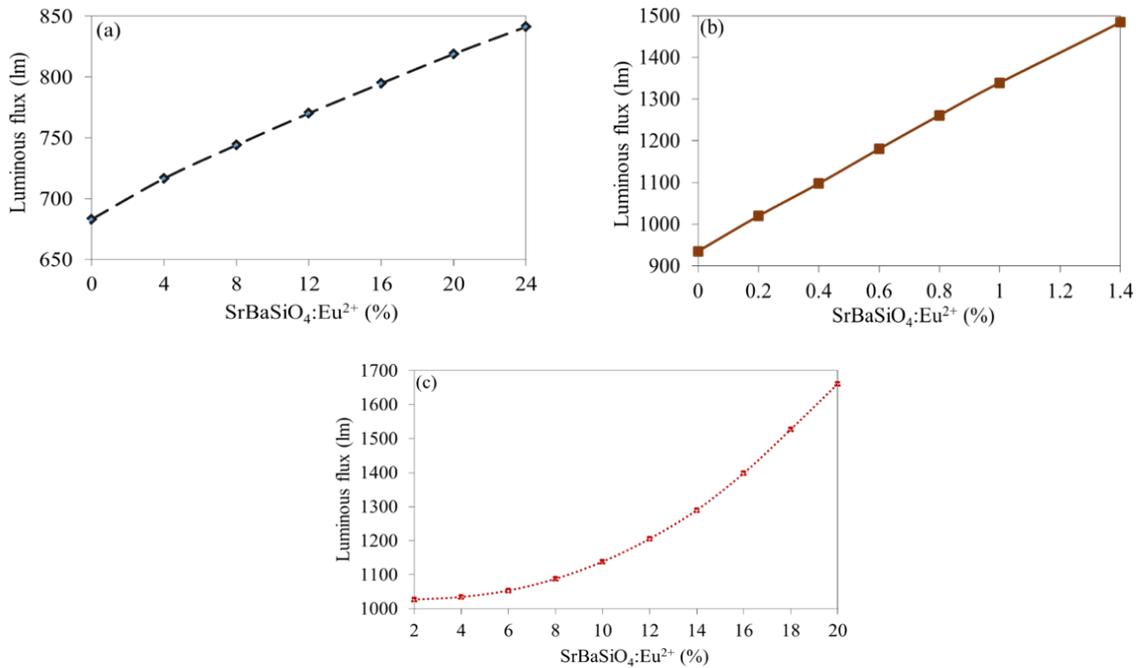


Figure 5. Luminous efficacy as a function of the concentration and size of SrBaSiO<sub>4</sub>:Eu<sup>2+</sup>: (a) CPG; (b) IPG; and (c) RPG

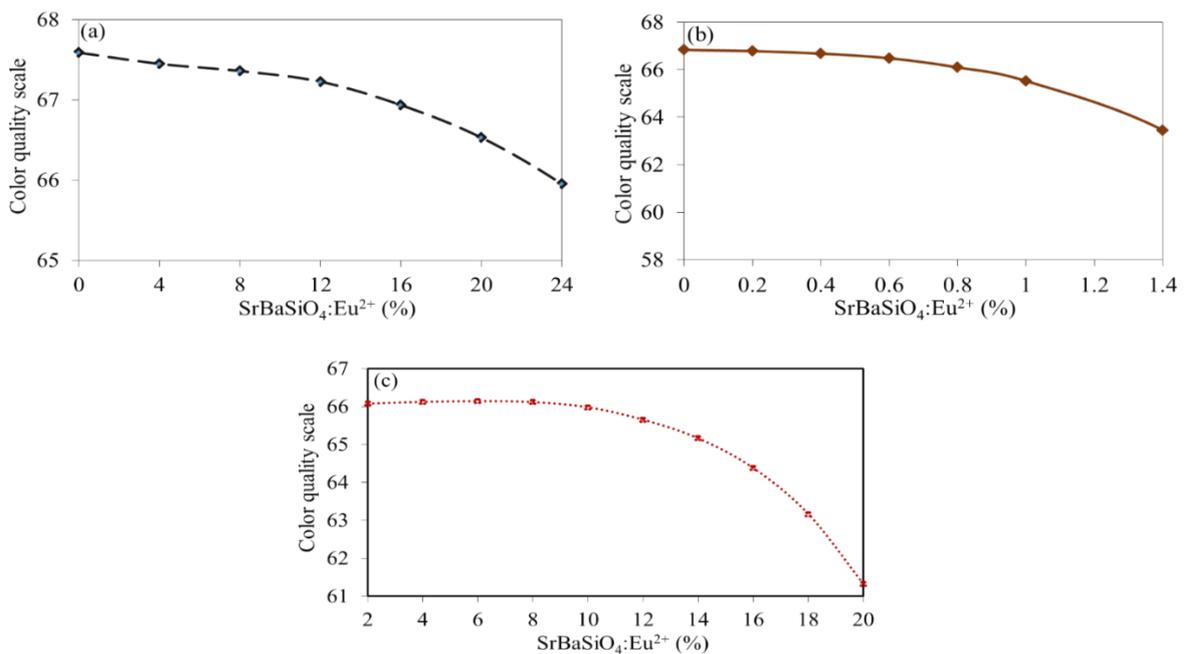


Figure 6. Color quality scale as a function of the concentration and size of SrBaSiO<sub>4</sub>:Eu<sup>2+</sup>: (a) CPG; (b) IPG; and (c) RPG

#### 4. CONCLUSION

In summary, the effectiveness of the yellow-green SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> in improving color quality and light output of WLEDs devices was verified through some references in the article. The experimental results from this research are also viable to conclude about the optical properties influences as follows. First, no matter what the average CCT value, color uniformity can be very diverse according to Mie scattering theory. This is the effect of light loss from scattering in white LED packages. Second, through Monte Carlo method, the luminous efficacy is confirmed to increase with SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> concentration. Particularly, the emitted light will grow as long as SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> concentration keep increasing at any phosphor geometry. Finally, selecting SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> phosphor is the appropriate solution for developing phosphorus materials as well as producing white LED packages. Although SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> phosphor is an effective enhancement material, the concentration of this phosphor must be monitored in application as any amount of SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> is good for lumen output and CCT deviation, however, CQS can be damaged if the SrBaSiO<sub>4</sub>:Eu<sup>2+</sup> concentration is too high. This research not only presented a new approach by applying the yellow-green phosphor to WLED but also compared the performance based on the type of phosphor geometry and phosphor concentration, which opens more options for manufacturers to develop their products and leaves valuable references for future studies.

#### REFERENCES

- [1] C. Tian, et al., "Mn<sup>4+</sup> activated Al<sub>2</sub>O<sub>3</sub> red-emitting ceramic phosphor with excellent thermal conductivity," *Optics Express*, vol. 27, no. 22, pp. 32666-32678, 2019.
- [2] J. Cheng, et al., "Photoluminescence properties of Ca<sub>4</sub>La<sub>6</sub>(SiO<sub>4</sub>)<sub>4</sub>(PO<sub>4</sub>)<sub>2</sub>O<sub>2</sub>-based phosphors for wLEDs," *Chinese Optics Letters*, vol. 17, no. 5, pp. 051602, 2019.
- [3] X. Liu, et al., "Upconversion luminescence, intrinsic optical bistability, and optical thermometry in Ho<sup>3+</sup>/Yb<sup>3+</sup>:BaMoO<sub>4</sub> phosphors," *Chin. Opt. Lett.*, vol. 17, no. 11, pp. 111601, 2019.
- [4] Shaojun, et al., "Energy transfer between Ce<sup>3+</sup> and Tb<sup>3+</sup> and the enhanced luminescence of a green phosphor SrB<sub>2</sub>O<sub>4</sub>:Ce<sup>3+</sup>, Tb<sup>3+</sup>, Na<sup>+</sup>," *Optical Materials Express*, vol. 6, no. 4, pp. 1172-1185, 2016.
- [5] Yang, et al., "Optical performance improvement of phosphor-in-glass based white light-emitting diodes through optimized packaging structure," *Applied Optics*, vol. 55, no. 29, pp. 8189-8195, 2016.
- [6] Zhengfa, et al., "Influence of co-doping Si ions on persistent luminescence of ZnGa<sub>2</sub>O<sub>4</sub>: Cr<sup>3+</sup> red phosphors," *Optical Materials Express*, vol. 6, no. 4, pp. 1329-1338, 2016.
- [7] Jia, et al., "Investigations on the luminescence of Ba<sub>2</sub>Mg(PO<sub>4</sub>)<sub>2</sub>:Eu<sup>2+</sup>, Mn<sup>2+</sup> phosphors for LEDs," *Optical Materials Express*, vol. 6, no. 11, pp. 3470-3475, 2016.
- [8] Jia, et al., "Generation of tunable-emission in Li<sub>4</sub>Ca<sub>1-x</sub>Sr<sub>0.96</sub> + x(SiO<sub>4</sub>)<sub>2.04</sub>Eu<sup>2+</sup> phosphors for LEDs application," *Optical Materials Express*, vol. 5, no. 8, pp. 1704-1714, 2015.
- [9] Huajuan, et al., "Close-relationship between the luminescence and structural characteristics in efficient nano-phosphor Y<sub>2</sub>Mo<sub>4</sub>O<sub>15</sub>:Eu<sup>3+</sup>," *Optical Materials Express*, vol. 5, no. 3, pp. 490-496, 2015.
- [10] Qi. D., et al., "Circadian-effect engineering of solid-state lighting spectra for beneficial and tunable lighting," *Optics Express*, vol. 24, no. 18, pp. 20049-20059, 2016.
- [11] Ruijin, et al., "Eu<sup>3+</sup>-activated CdY<sub>4</sub>Mo<sub>3</sub>O<sub>16</sub> nanoparticles with narrow red-emission and broad excitation in near-UV wavelength region," *Optical Materials Express*, vol. 6, no. 11, pp. 2397-2403, 2016.
- [12] Luting, et al., "Luminescent properties of novel red-emitting phosphor: Gd<sub>2</sub>O<sub>2</sub>CN<sub>2</sub>:Eu<sup>3+</sup>," *Optical Materials Express*, vol. 5, no. 11, pp. 2616-2624, 2015.
- [13] Yumiko, et al., "Persistent luminescence properties of Cr<sup>3+</sup>-Sm<sup>3+</sup> activated LaAlO<sub>3</sub> perovskite," *Optical Materials Express*, vol. 6, no. 5, pp. 1500-1505, 2016.
- [14] Y. J. Park, et al., "Development of high luminous efficacy red-emitting phosphor-in-glass for high-power LED lighting systems using our original low T<sub>g</sub> and T<sub>s</sub> glass," *Opt. Lett.*, vol. 44, no. 24, pp. 6057-6060, 2019.
- [15] L. Yang, et al., "Thermally stable lead-free phosphor in glass enhancement performance of light emitting diodes application," *Appl. Opt.*, vol. 58, pp. 4099-4104, 2019.
- [16] T. Wei, Wang et al., "Single Pr<sup>3+</sup>-activated high-color-stability fluoride white-light phosphor for white-light-emitting diodes," *Opt. Mater. Express*, vol. 9, no. 1, pp. 223-233, 2019.
- [17] Xiaona, et al., "Color-tunable upconversion photoluminescence and highly performed optical temperature sensing in Er<sup>3+</sup>/Yb<sup>3+</sup> co-doped ZnWO<sub>4</sub>," *Optics Express*, vol. 24, no. 20, pp. 22438-22447, 2016.
- [18] Song, et al., "Luminescence characteristics of the Ce<sup>3+</sup>-doped garnets: the case of Gd-admixed Y<sub>3</sub>Al<sub>5</sub>O<sub>12</sub> transparent ceramics," *Optical Materials Express*, vol. 5, no. 12, pp. 2902-2910, 2015.
- [19] Huang, et al., "Liquid-crystal-modulated correlated color temperature tunable light-emitting diode with highly accurate regulation," *Optics Express*, vol. 23, no. 3, pp. A149-A156, 2015.
- [20] Qi Hong, et al., "High-efficiency quantum dot remote phosphor film," *Applied Optics*, vol. 54, no. 15, pp. 4617-4622, 2015.
- [21] Cunlong, et al., "Highly pure green light emission of perovskite CsPbBr<sub>3</sub> quantum dots and their application for green light-emitting diodes," *Optics Express*, vol. 24, no. 13, pp. 15071-15078, 2016.
- [22] Oh Kwon, et al., "White luminescence characteristics of red/green silicate phosphor-glass thick film layers printed on glass substrate," *Optical Materials Express*, vol. 6, no. 3, pp. 938-945, 2016.

- [23] Le Wang, et al., "Highly efficient narrow-band green and red phosphors enabling wider color-gamut LED backlight for more brilliant displays," *Optics Express*, vol. 23, no. 22, pp. 28707-28717, 2015.
- [24] Vineet, et al., "Efficient Color Tunable ZnWO<sub>4</sub>:Er<sup>3+</sup>-Yb<sup>3+</sup> Phosphor for High Temperature Sensing," *Journal of Display Technology*, vol. 12, no. 11, pp. 1472-1477, 2016.
- [25] L. Duan, et al., "Wide color gamut display with white and emerald backlighting," *Appl. Opt.*, vol. 57, pp. 1338-1344, 2018.
- [26] Wang, et al., "Accurate control of chromaticity and spectra by feedback phosphor-coating," *Optics Express*, vol. 23, no. 9, pp. 11576-11585, 2015.
- [27] S. Bindai, et al., "Realization of phosphor-in-glass thin film on soda-lime silicate glass with low sintering temperature for high color rendering white LEDs," *Appl. Opt.*, vol. 58, pp. 2372-2381, 2019.
- [28] Jagjeet, et al., "Luminescence Studies on Ba<sub>2</sub>MgSi<sub>2</sub>O<sub>7</sub> Doped With Eu<sup>2+</sup> and Tm<sup>3+</sup> Phosphors," *Journal of Display Technology*, vol. 12, no. 5, pp. 460-465, 2016.
- [29] Jonas, et al., "Persistent phosphor SrAl<sub>2</sub>O<sub>4</sub>:Eu,Dy in outdoor conditions: saved by the trap distribution," *Optics Express*, vol. 23, no. 15, pp. A868-A881, 2015.
- [30] Yahong, et al., "Luminescent properties of a green long persistent phosphor Li<sub>2</sub>MgGeO<sub>4</sub>:Mn<sup>2+</sup>," *Optical Materials Express*, vol. 6, no. 3, pp. 929-937, 2016.
- [31] Zhongyang, et al., "Enhanced forward emission of YAG:Ce<sup>3+</sup> phosphor with polystyrene nanosphere coating," *Applied Optics*, vol. 54, no. 19, pp. 6025-6028, 2015.
- [32] F. B. Chen, et al., "Investigation on Modulation Speed of Photon-Recycling White Light-Emitting Diodes with Vertical-Conduction Structure," *J. Lightwave Technol.*, vol. 37, no. 4, pp. 1225-1230, 2019.
- [33] R. Q. Wan, et al., "Simultaneously improve the luminous efficiency and color-rendering index of GaN-based white-light-emitting diodes using metal localized surface plasmon resonance," *Optics Letters*, vol. 44, no. 17, pp. 4155-4158, 2019.
- [34] S. K. Abeysekera, et al., "Impact of circadian tuning on the illuminance and color uniformity of a multichannel luminaire with spatially optimized LED placement," *Opt. Express*, vol. 28, no. 1, pp. 130-145, 2020.
- [35] Q. W. Xu, et al., "Nanocrystal-filled polymer for improving angular color uniformity of phosphor-converted white LEDs," *Appl. Opt.*, vol. 58, no. 27, pp. 7649-7654, 2019.