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$Sr_2Si_5N_8:Eu^{2+}$ phosphor: a novel recommendation for improving the lighting performance of the 7000 K remote-packaging white LEDs

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Abstract. In the last few years, white LED lamps (WLEDs) have been popularly used in general lighting because of some excellent properties, such as fast response time, environment friendliness, small size, long lifetime, and high efficiency. In this research, we propose a novel recommendation for improving the lighting performance (in terms of the colour rending index, colour quality scale, and luminous efficiency) of the 7000 K remote-packaging WLEDs by adding the red-emitting $Sr_2Si_5N_8:Eu^{2+}$ phosphor to the yellow-emitting YAG:Ce phosphor compound. In the first stage, we use MATLAB to investigate the light scattering process based on Mie Theory. After that, we use the Light Tool software to simulate and demonstrate this process. Finally, the simulation results are verified with analytical analysis, which clearly shows that the lighting performance of the 7000 K remote-packaging WLEDs significantly depended on the $Sr_2Si_5N_8:Eu^{2+}$ concentration. The results provided a potential practical solution for manufacturing remote phosphor WLEDs in the near future.

Key words: remote-packaging WLEDs, red-emitting $Sr_2Si_5N_8:Eu^{2+}$ phosphor, colour rendering index, colour uniformity, lumen output.

1. INTRODUCTION

Nowadays, white light-emitting diodes (WLEDs) are considered as the latest type of solid-state lighting, which have unique advantages in comparison with other eight sources [1–3]. Being considered as the fourth generation of light sources, WLEDs have the following advantages: environment friendliness, wide operation temperature, long lifetime, wide range of colour temperatures, energy saving compared to other light sources, and quick startup [1–4]. Commonly, there are two primary ways of producing high-intensity white light using LEDs. One is to use individual LEDs that emit three primary colours – red, green, and blue – and then mix them all to form white light. The other is to use a phosphor material to convert a monochromatic light from a blue or UV LED to a broad-spectrum white light, much in the same way as a fluorescent light bulb works [1–4]. The second method has had a huge advance and is widely used in the public lighting due to the low cost and simple technology of production and use. Furthermore, the blue light from the blue LEDs chip

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should be converted into white light by packaging for the second method. From this point of view, the LEDs packaging is considered as an important research direction for improving the lighting performance of WLEDs. A packaging method in LEDs not only can ensure better performance of LED devices by enhancing their reliability and optical characteristics but can also realize control and adjustment of the final lighting performance [4–6]. In the last decade, many papers have focused on improving the lighting performance of WLEDs by improving the packaging method. In more details, lighting properties of WLEDs were enhanced by $Sr_{1-x}Ba_xSi_2O_2N_2:Eu^{2+}$(0 x 1) [7], β-SiAlON:$Yb^{2+}$ phosphor [8], novel packaging structures [9], $Li_2SrSiO_4:Eu^{3+}$, Sm^{3+} [10], or by adding red or green phosphor [11,12] into the phosphor layer of WLEDs. We can see that this research direction is too hot today.

On another side, the remote-packaging WLEDs are a structure in which the phosphor is moved far away from the LED chip. This structure could significantly reduce the probability of the absorption of the re-emitted light by the WLEDs chip, and thus improve the phosphor efficiency. With these advances, the remote phosphor structure of WLEDs seems to be a solution for the manufacture of WLEDs [13–15]. However, very rare works have improved and demonstrated the lighting performance of WLEDs with a remote phosphor structure by mixing two or more diffusive particles into the phosphor compound. It is the remaining gap that could be filled by this research work.

In the last decade, SiN_4-based covalent nitride materials such as $M_2Si_5N_8:Eu^{2+}$ and $MAlSiN_3:Eu^{2+}$ (M = Ca, Sr, Ba) have been extensively considered as excellent materials for the LEDs technology. Among these phosphors, $Sr_2Si_5N_8:Eu^{2+}$ showed excellent emission characteristics under a blue excitation wavelength of 450 nm, had a uniform particle size distribution, and high performance in LED packages [16–18].

In this research, $Sr_2Si_5N_8:Eu^{2+}$ particles were remotely added into the yellow-emitting YAG:Ce phosphor of the remote-packaging WLEDs in order to improve the lighting performance of WLEDs. Based on Light Tools and MATLAB software, a favourable influence of $Sr_2Si_5N_8:Eu^{2+}$ on the lighting performance of the remote-packaging WLEDs is suggested, investigated, and demonstrated. The following can be considered as the main contributions of this paper:

(1) The 7000 K remote-packaging WLEDs are proposed and simulated by Light Tools.
(2) The scattering properties of $Sr_2Si_5N_8:Eu^{2+}$ particles are investigated by MATLAB.
(3) The influence of $Sr_2Si_5N_8:Eu^{2+}$ concentration on the lighting performance (in terms of correlated colour temperature deviation (D-CCT), Colour Rending Index (CRI), Colour Quality Scale (CQS), and the luminous efficacy) is investigated.

The remaining part of this paper is organized as follows. The system model and mathematical description are simulated and proposed in Section 2. Section 3 presents the results and some discussion. Section 4 concludes this paper.

2. SYSTEM MODEL AND MATHEMATICAL DESCRIPTION

In this research, 7000 K remote-packaging WLEDs were simulated by using Light Tools (Fig. 1). This model of remote-packaging WLEDs has the following key parameters:

(1) The parameters of the reflector: an 8 mm bottom length, a 2.07 mm height, and a 9.85 mm length.
(2) The remote phosphor layer has a fixed thickness of 0.08 mm.
(3) The parameters of the LED chip: a 1.14 mm square base and a 0.15 mm height. Each blue chip has a 1.16 W luminous flux [10–11].

In the simulation, we set the $Sr_2Si_5N_8:Eu^{2+}$ concentration from 2% to 22%. The refractive indexes of $Sr_2Si_5N_8:Eu^{2+}$, yellow-emitting phosphors, and the silicone glue were chosen as 1.80, 1.83, and 1.50, respectively. The selected average radius of the phosphor particles was at 7.25 μm. The diffusional particle density was varied to fix the average correlated colour temperature (CCT) value. When the weight percentage of the diffusers was increased, it was necessary to reduce the weight percentage of YAG:Ce phosphor to maintain the average CCT value [10–11].

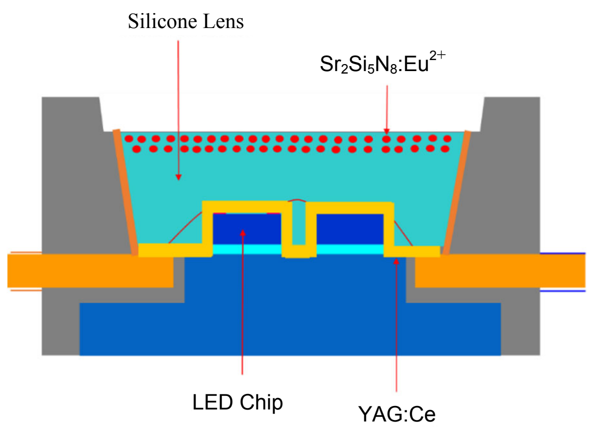

Fig. 1. Physical structure of 7000 K remote-packaging WLEDs.

Applying Mie theory [17,18], we can formulate:

- the scattering coefficient $\mu_{sca}(\lambda)$:

$$\mu_{\text{sca}}(\lambda) = \int N(r) C_{\text{sca}}(\lambda, r) dr; \qquad (1)$$

- the anisotropy factor $g(\lambda)$:

$$g(\lambda) = 2\pi \int \int_{-1}^{1} p(\theta, \lambda, r) f(r) \cos\theta d \cos\theta dr; \qquad (2)$$

- the reduced scattering coefficient $\delta_{sca}(\lambda)$:

$$\delta_{\text{sca}} = \mu_{\text{sca}}(1 - g). \qquad (3)$$

In these equations, $N(r)$ indicates the distribution density of diffusional particles (mm^3); C_{sca} is the scattering cross sections (mm^2), $p(\theta,\lambda,r)$ is the phase function, λ is the light wavelength (nm), r is the radius of diffusional particles (µm), θ is the scattering angle (°), and $f(r)$ is the size distribution function of the diffuser in the phosphorous layer.

3. RESULTS AND DISCUSSION

The scattering and reduced scattering coefficients of the $Sr_2Si_5N_8:Eu^{2+}$ particles, obtained with using MATLAB software, are presented in Fig. 2 and Fig. 3, respectively. From this analysis, we can see that the scattering coefficients grew with increasing $Sr_2Si_5N_8:Eu^{2+}$ concentration (Fig. 2). This means that the white-light quality can be enhanced by controlling the $Sr_2Si_5N_8:Eu^{2+}$ concentration. The scattering effects of $Sr_2Si_5N_8:Eu^{2+}$ particles were significantly influenced on remote-packaging WLEDs (Fig. 2). The $Sr_2Si_5N_8:Eu^{2+}$ phosphor has a higher absorption ability for the blue light from LEDs. Therefore, the domination of the emitted red light could be applied for compensating red light in remote packaging WLEDs. Moreover, the reduced scattering coefficients of $Sr_2Si_5N_8:Eu^{2+}$ at wavelengths 453 nm, 555 nm, and 680 nm are approximately equal to each other (Fig. 3). This indicates that the scattering stability of $Sr_2Si_5N_8:Eu^{2+}$ is useful for controlling the colour quality of the remote packaging WLEDs.

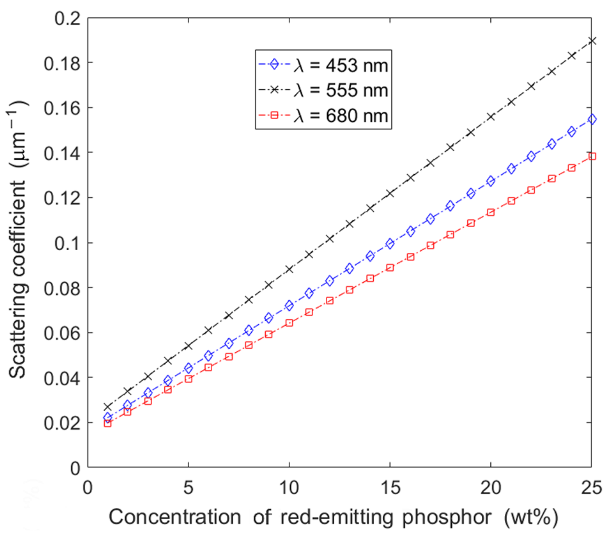

Fig. 2. Scattering coefficients of $Sr_2Si_5N_8:Eu^{2+}$ phosphor.

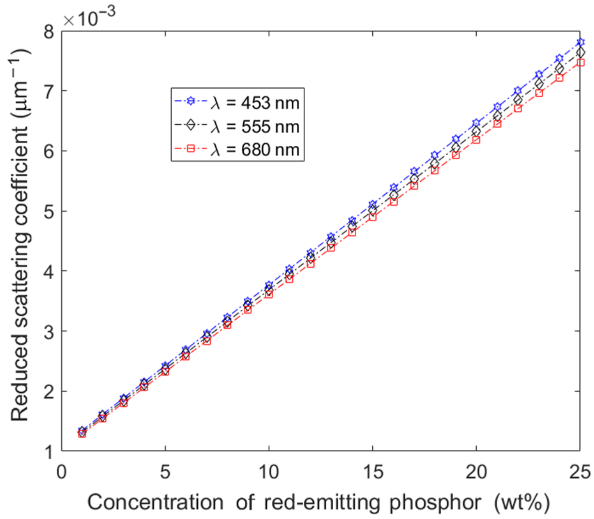

Fig. 3. Reduced scattering coefficient of $Sr_2Si_5N_8:Eu^{2+}$ phosphor.

The ΔCCT of the 7000 K remote-packaging WLEDs at different concentrations of $Sr_2Si_5N_8:Eu^{2+}$ phosphor particles (2–22%) was determined by using Light Tools (Fig. 4). The influence of particle concentration on the colour rendering index (CRI) and the colour quality scale (CQS) is illustrated in Fig. 5 and Fig. 6, respectively. As we can see, the CRI increased from 68 to 75 and the CQS from 64 to 68 while the concentration of $Sr_2Si_5N_8:Eu^{2+}$ rose continuously from 2% to 22%.

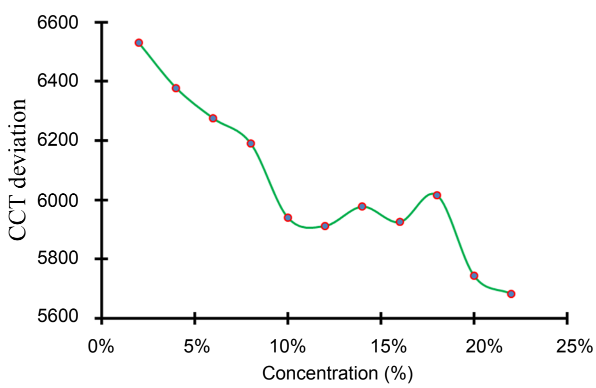

Fig. 4. Colour–temperature (CCT) deviation of the remote-packaging WLEDs at adding red-emitting $Sr_2Si_5N_8:Eu^{2+}$ phosphor particles.

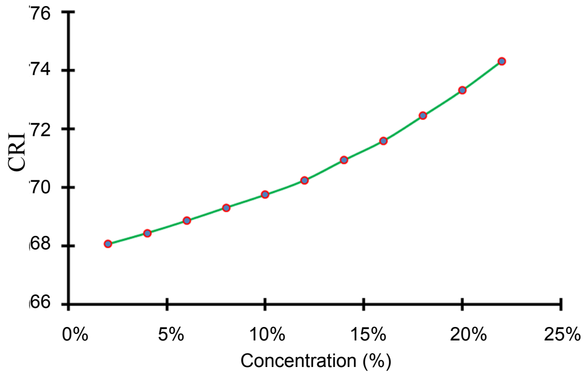

Fig. 5. Growth of the Colour Rendering Index (CRI) of the remote-packaging WLEDs at adding red-emitting $Sr_2Si_5N_8:Eu^{2+}$ phosphor particles.

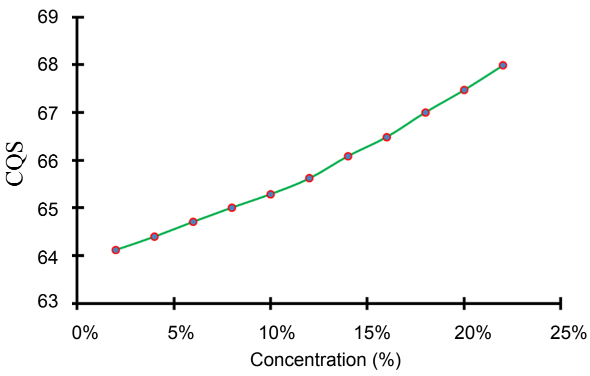

Fig. 6. Growth of the Colour Quality Scale (CQS) of the remote-packaging WLEDs at adding red-emitting $Sr_2Si_5N_8:Eu^{2+}$ phosphor particles.

The highest values of the CRI and CQS were respectively about 75 and 68 at the 20% $Sr_2Si_5N_8:Eu^{2+}$ phosphor concentration. The D-CCT of WLEDs decreased significantly, from 6600 K to 5700 K, at the increasing concentration of $Sr_2Si_5N_8:Eu^{2+}$ phosphor particles and reached the lowest value at the 12–22% $Sr_2Si_5N_8:Eu^{2+}$ phosphor concentration (Fig. 4). The decrease of the D-CCT at the increasing concentration of the $Sr_2Si_5N_8:Eu^{2+}$ particles could be caused by the overscattering properties of light from the blue chips in the phosphor layer. There are maximums and valleys on the trendline because the scattering process in the phosphor layer is a random process and may be caused by some significant changes in some simulation point in the trendline. The lighting performance of the 7000 K remote-packaging WLEDs is influenced by each light (from the blue chips) scattering process in the phosphor compounding.

The influence of the red-emitting phosphor concentration on the luminous efficacy of the 7000 K WLEDs

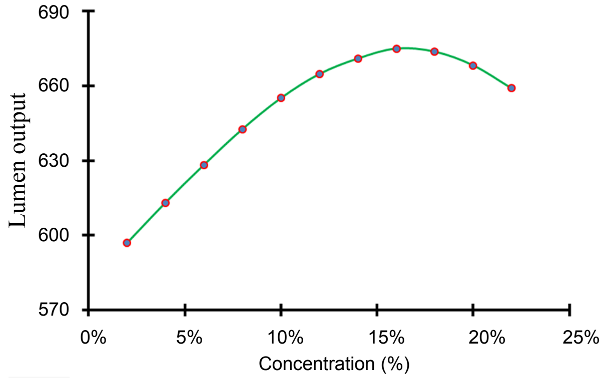

Fig. 7. Lumen output of the remote-packaging WLEDs at adding red-emitting $Sr_2Si_5N_8:Eu^{2+}$ phosphor particles.

is presented in Fig. 7. The figure shows that the luminous efficacy increased significantly from 600 lm to 680 lm while the concentration of $Sr_2Si_5N_8:Eu^{2+}$ phosphor was increased from 2% to 16%. After that, the lumen output had a considerable decrease to 660 lm as the concentration of $Sr_2Si_5N_8:Eu^{2+}$ phosphor increased to 18–20%. The lumen output can reach the highest value at 16% to 18% $Sr_2Si_5N_8:Eu^{2+}$ phosphor. This effect was caused by the overscattering and backscattering process in WLEDs when the concentration of the red-emitting phosphor was higher than 18%. The overscattering process was linked to the lost energy of the light and the decrease of the luminous efficacy of the WLEDs.

4. CONCLUSIONS

The use of the red-emitting $Sr_2Si_5N_8:Eu^{2+}$ phosphor particles to improve the lighting performance of 7000 K remote-packaging WLEDs was suggested and its influence was analysed. From the results and theoretical analysis, some conclusions can be drawn:

(1) Colour uniformity (CCT deviation) significantly decreased (from 6600 K to 5700 K) with the rising concentration of $Sr_2Si_5N_8:Eu^{2+}$ phosphor particles.

(2) The values of CRI and CQS increased from 68 to 75 and from 64 to 68, respectively, while the concentration of $Sr_2Si_5N_8:Eu^{2+}$ phosphor rose continuously from 2% to 22%. The highest values of CRI and CQS (75 and 68) were at 22% $Sr_2Si_5N_8:Eu^{2+}$ phosphor concentration.

(3) The lumen output had an increase from 600 lm to 680 lm, then a decrease to 660 lm after the optimal value. The lumen output had a massive decrease of 18–20% $Sr_2Si_5N_8:Eu^{2+}$ phosphor. The highest value of the lumen output was recorded at 16% to 18% $Sr_2Si_5N_8:Eu^{2+}$ phosphor.

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$Sr_2Si_5N_8:Eu^{2+}$ fosfoor: uudne soovitus 7000 K kaugpakendatud valge valgusdioodi (WLED) valgustamisomaduste täiustamiseks

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Viimastel aastatel on valged valgusdioodvalgustid (WLED) üldvalgustites väga populaarseks saanud. Põhjuseks on nende valgustite väike ümberlülitusaeg, keskkonnasõbralikkus, väikesed mõõtmed, pikk kasutusiga ja suur kasutegur. Käesolevas uurimuses on esitatud uudne soovitus nende dioodvalgustite valgustamisomaduste (värvuse ümberpaigutamise indeksi (CRI), värvuse kvaliteediastmiku (CQS), valgusjõu efektiivsuse) täiustamiseks rakendatuna 7000 K kaugpakendatud valgele valgusdioodile, lisades punast fosfoori $Sr_2Si_5N_8:Eu^{2+}$ kollasele põhiühendile YAG:Ce. Soovituse aluseks on programmiga MATLAB tehtud simulatsioonid, kasutades Mie teooriat valguse hajususe kohta. Hajumisprotsesside täpsustamiseks on kasutatud ka programmi Light Tool.

On näidatud, et uuritud valge valgusdioodi omadused on parendatavad fosfoori $Sr_2Si_5N_8:Eu^{2+}$ lisamisega ja valgusdioodi valgustamisomadused sõltuvad fosfoori kontsentratsioonist. Soovitus pakub praktilist abi 7000 K kaugpakendatud valge valgusdioodi (WLED) valgustamisomaduste täiustamiseks.