

Improving optical performance of multi-chip white LEDs by bi-layers remote-packaging phosphors

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In the last some decades, White LEDs (WLEDs) with the optimal advances such as durability, chromatic performance, low-power consumption, long-lifetime, and environmentally friendliness are popularly used in industrial and general lighting all over the world. From this point of view, we present an innovative coating model for the multi-chip White LEDs (MCW-LEDs) in a direction to improving their optical performance. This model base on the WLEDs with bi-layers Red-Emitting and Yellow-Emitting Phosphor, which is set up remotely from the blue WLEDs chip. With using the Mat lab and the industrial Light Tools software, the optical performance of the WLEDs could be improved significantly by the bi-layer remote-packaging phosphors. Furthermore, the research results indicated that the proposed coating model of MCW-LEDs could be a prospective solution for manufacturing remote-packaging WLEDs in the near future.

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1. Introduction

Nowadays, light-emitting diodes (LEDs) have remarkable progress in all over the world and has huge study attention in the connection to their optimal characteristics (small size, high reliability, low-power consumption, and long life). In the trend of packaging technology and material development, the luminous efficacy and optical properties of LEDs have been increased significantly. Now, it can directly compete with the fluorescent lamp, incandescent lamp, and high-pressure sodium lamp not only in general lighting but also in the all living area [1-3]. In the LEDs industry, the first phosphor-converted LEDs in which white light is obtained by mixing the emitted blue light from the GaN chip with the broad and yellow light excited by YAG:Ce phosphor. Moreover, many research works focused on phosphor-converting processes to improve the optical performance of white LEDs (WLEDs). Some researchers would like to improve the optical properties of WLEDs by optimization of phosphor thickness, concentration, particle size, geometry, amount, and arrangement. In result, packaging method of WLEDs plays significant roles in improving the optical properties because of reducing the light trapping in WLEDs [1]. On the other ways, some papers just concentrated on doping green or red phosphor into the phosphor compounding to improve lighting performance of WLEDs. Moreover, in [2] TiO₂ was doping to phosphor compounding to enhancing lighting performance of WLEDs, in [3,4] Red-emitting α -SrO·3B₂O₃:Sm²⁺ phosphor was used for the similar

purpose. With these directions, some kinds of phosphor structures were used such as conformal, in-cup, doom, and remote phosphor. From the research results, the remote-packaging phosphor geometry structure has critical advances in comparison with others structures. The remote phosphor structure of WLEDs is a structure in which the phosphor layers are moved far away from the LED chip. This structure could significantly decrease the probability of absorption of the re-emitted light by the WLEDs chip and then improve the phosphor efficiency. With these advances, the remote packaging WLEDs can be proposed as a prospective solution for manufacture WLEDs in the future time [5-12].

In last twenties years, SiN₄-base covalent nitride materials such as M₂Si₅N₈:Eu²⁺ and MAiSiN₃:Eu²⁺ (M= Ca, Sr, Ba) have been extensively considered as excellent materials for LEDs technology. Among these phosphors, Sr₂Si₅N₈:Eu²⁺ presented excellent emission characteristics under a blue excitation wavelength of 450 nm, had a uniform particle size distribution and showed high performance in LED packages [13-16]. Besides, with the advantages of excellent thermal and chemical stability, Sr₂Si₅N₈:Eu²⁺ could be employed for compensating red-light, resulting in increasing the color quality of LED lamps. However, until now, there are too little previous studies which employ Sr₂Si₅N₈:Eu²⁺ for remote-packaging WLEDs.

In this work, the effect of bi-layer remote Red-Emitting Sr₂Si₅N₈:Eu²⁺ Phosphor and Yellow-Emitting YAG:Ce Phosphor on the optical performance of MCW-LEDs was investigated. In this structure, the lower layer is

Red-Emitting $\text{Sr}_2\text{Si}_5\text{N}_8:\text{Eu}^{2+}$ Phosphor and the upper is Yellow-Emitting YAG:Ce Phosphor. The main contributions of this research could be summarized as the following:

1) The innovative model of the remote-packaging LEDs with the bi-layer remote phosphor is proposed and simulated by Light Tools and Mat Lab software.

2) The influence of the concentration of the red-emitting phosphor on the optical performance of the remote-packaging WLEDs is demonstrated and convinced.

3) Bi-layer remote Red-Emitting $\text{Sr}_2\text{Si}_5\text{N}_8:\text{Eu}^{2+}$ Phosphor and Yellow-Emitting YAG:Ce Phosphor could be proposed as a promised solution for LEDs manufacture.

The rest of this paper can be organized as follow. Section 2 presents the proposed model and mathematical analysis of the remote-packaging WLEDs. Then section 3 gives the results and some discussions. Finally, section 4 concludes this paper.

2. Model and method

In this section, the real 7000 K remote-packaging WLEDs with LED chips was used to simulate the physical model by the commercial Light Tools software (Fig. 1). For the simulation model, there are the critical parameters of the real RP-WLEDs:

- Each blue LED chip with a 1.14 mm square base and a 0.15 mm height is bonded to the reflector. The power of each blue chip is 1.16 W

- The reflector has a bottom length of 8 mm, a height of 2.07 mm and a length of 9.85 mm.

- The remote phosphor compounding has the fixed thickness 0.08 mm, which covers the nine chips [14].

In this simulation, the refractive indexes of the red-emitting $\text{Sr}_2\text{Si}_5\text{N}_8:\text{Eu}^{2+}$ and YAG:Ce phosphors are set at 1.93 and 1.83, respectively. The silicone glue has the refractive index of 1.5. The average radius of two types of phosphors is chosen as $7.25\mu\text{m}$ for all simulation stages. In this calculation, the concentration of the red-emitting $\text{Sr}_2\text{Si}_5\text{N}_8:\text{Eu}^{2+}$ phosphor was changed from 0% to 11 % while the yellow YAG:Ce phosphor concentration was fixed at 15%.

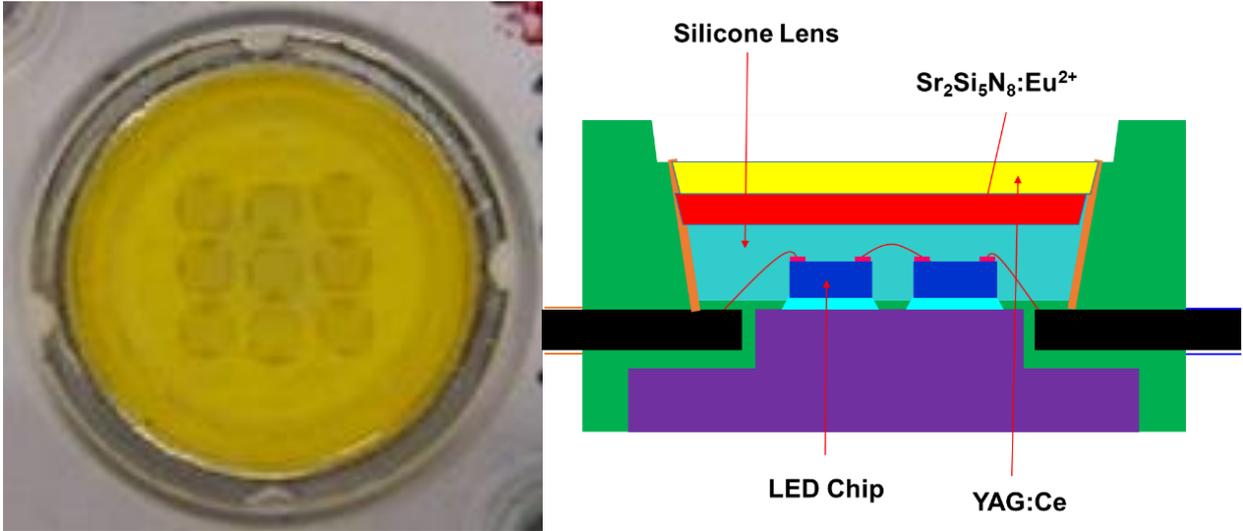


Fig. 1. The remote-packaging WLEDs

The mathematical description could be demonstrated by Mat lab software using Mie-scattering theory [17]. The scattering coefficient $\mu_{sca}(\lambda)$, anisotropy factor $g(\lambda)$, and reduced scattering coefficient $\delta_{sca}(\lambda)$ are formulated by the followings:

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

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

$$\delta_{sca} = \mu_{sca}(1-g), \quad (3)$$

where $N(r)$ is the number density, C_{sca} is the scattering cross sections (per square millimeter), $p(\theta, \lambda, r)$ is the phase

function, λ is the wavelength of the incident light (nanometers), r is the radius of particles (micrometers), θ is the scattering angle (degree), and $f(r)$ is the size distribution function of the diffusers in the phosphor layer.

$$f(r) = f_{dif}(r) + f_{phos}(r), \quad (4)$$

$$N(r) = N_{dif}(r) + N_{phos}(r) = K_N \cdot [f_{dif}(r) + f_{phos}(r)] \quad (5)$$

$N(r)$ is composed of the diffusive particle number density $N_{dif}(r)$ and the phosphor particle number density $N_{phos}(r)$. $f_{dif}(r)$ and $f_{phos}(r)$ are the size distribution function data of the diffusor and phosphor particle. If the phosphor concentration c (milligrams per cubic millimeter) of the

mixture is known, K_N is the number of the unit diffuser for one diffuser concentration, and K_N can be calculated by:

$$c = K_N \int M(r) dr. \quad (6)$$

Below equation can calculate $M(r)$:

$$M(r) = \frac{4}{3} \pi r^3 [\rho_{diff} f_{diff}(r) + \rho_{phos} f_{phos}(r)], \quad (7)$$

where $\rho_{diff}(r)$ and $\rho_{phos}(r)$ are the density of diffuser and phosphor crystal.

In Mie theory, C_{sca} is normally presented:

$$C_{sca} = \frac{2\pi}{k^2} \sum_0^{\infty} (2n-1) (|a_n|^2 + |b_n|^2), \quad (8)$$

where k is the wavenumber ($2\pi/\lambda$), and a_n and b_n are the expansion coefficients with even symmetry and odd symmetry, respectively. These coefficients can be calculated by equations below:

$$a_n(x, m) = \frac{\psi'_n(mx)\psi_n(x) - m\psi_n(mx)\psi'_n(x)}{\psi'_n(mx)\xi_n(x) - m\psi_n(mx)\xi'_n(x)}, \quad (9)$$

$$b_n(x, m) = \frac{m\psi'_n(mx)\psi_n(x) - \psi_n(mx)\psi'_n(x)}{m\psi'_n(mx)\xi_n(x) - \psi_n(mx)\xi'_n(x)}, \quad (10)$$

where x is the size parameter ($= k.r$), m is the refractive index of the diffusive scattering particles, $\psi_n(x)$, $\xi_n(x)$ are the Riccati - Bessel function. For small spheres, the phase function $p(\theta, \lambda, r)$ can be calculated by [17]:

$$p(\theta, \lambda, r) = \frac{4\pi\beta(\theta, \lambda, r)}{k^2 C_{sca}(\lambda, r)}, \quad (11)$$

where $\beta(\theta, \lambda, r)$ is the dimensionless scattering function, which is obtained by the scattering amplitude functions S_1 and S_2 :

$$\beta(\theta, \lambda, r) = \frac{1}{2} [|S_1(\theta)|^2 + |S_2(\theta)|^2], \quad (12)$$

$$S_1 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[a_n(x, m)\pi_n(\cos\theta) + b_n(x, m)\tau_n(\cos\theta) \right], \quad (13)$$

$$S_2 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[a_n(x, m)\tau_n(\cos\theta) + b_n(x, m)\pi_n(\cos\theta) \right]. \quad (14)$$

In equations (13) and (14), the angular dependent functions $\pi_n(\cos\theta)$ and $\tau_n(\cos\theta)$ are expressed in the angular scattering patterns of the spherical harmonics [17-21].

3. Results and discussion

The scattering, reduced scattering, and backscattering of light inside two phosphor layers are calculated and demonstrated using Mat lab software as shown in Fig. 2 and 3. From Fig. 2 and Fig. 3, indicate that the scattering and reduced scattering coefficients of blue light ($\lambda = 455\text{nm}$), and yellow light ($\lambda = 595\text{nm}$) had a rapid rise, respectively. Moreover, scattering coefficient and reduced scattering coefficient of blue light increase higher than those of yellow light in both red and yellow phosphor layers of the WLEDs. Furthermore, backscattering coefficient of wavelength 455 nm in red phosphor layer is much higher than that of wavelength 595 nm in yellow phosphor layer (Fig. 4a) [14].

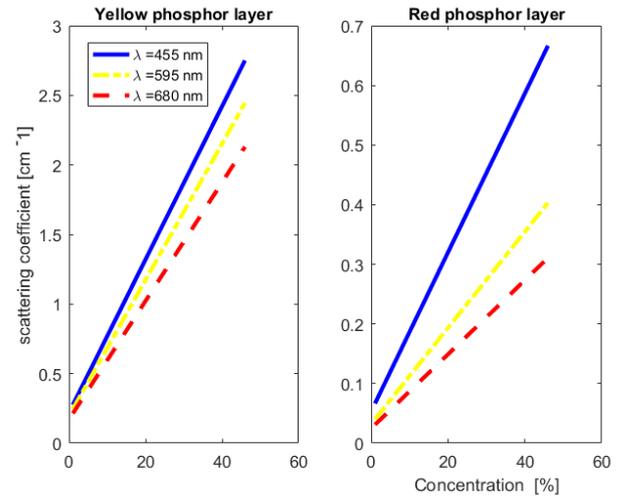


Fig. 2. Scattering coefficient of two phosphor layers of 455 nm, 595 nm wavelengths

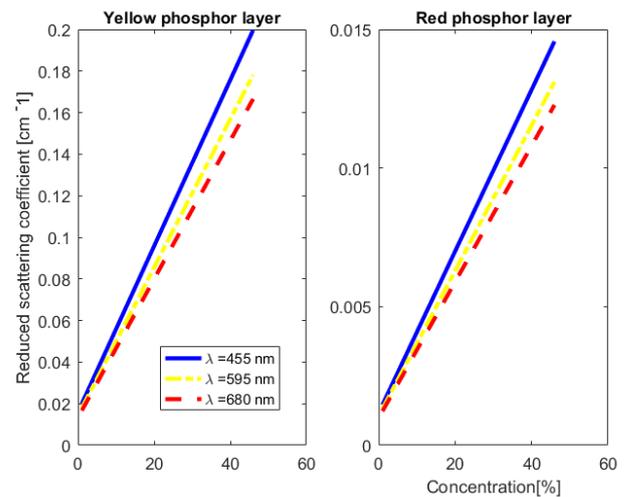


Fig. 3. Reduced scattering coefficient of two phosphor layers of 455 nm, 595 nm wavelengths.

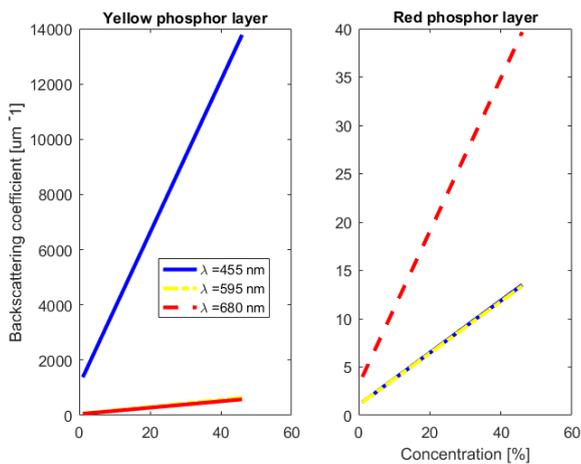


Fig. 4. Backscattering coefficient of two phosphor layers of 455 nm, 595 nm wavelengths

The results from the theory-based calculation and optical ray-tracing spectra with Light Tools agreed on each other well. With the increase of red phosphor concentrations from 0% to 11%, the CRI and CQS moved up (Fig. 5). In this situation, the CRI had a considerable increase from 67 to 80. Furthermore, the color quality scale (CQS) rose up from 64 to 77 in Fig. 6. This results indicated that for two layers LED packages the chromaticity of LED can be efficiently adjusted by the ratio of blue to yellow and red components since the yellow phosphor does not absorb the backscattering of red emission from the upper red phosphor layer. It is meant that the emission energy loss is associated with re-absorption process by different phosphor emission spectrum within the LED packages.

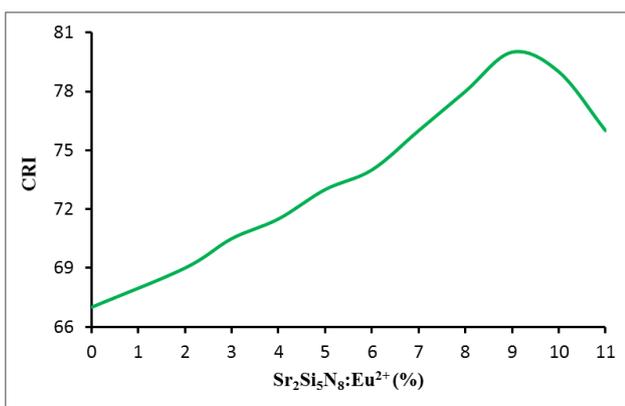


Fig. 5. The CRI of two phosphor layers remote-packaging WLEDs

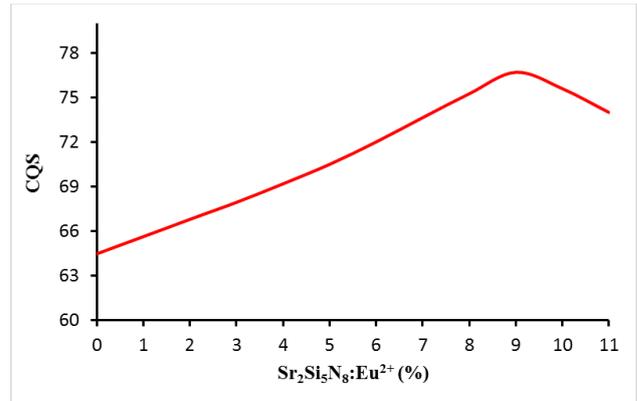


Fig. 6. The CQS of two phosphor layers remote-packaging WLEDs

4. Conclusion

In this paper, the remote-packaging WLEDs with bi-layer Red-Emitting $\text{Sr}_2\text{Si}_5\text{N}_8:\text{Eu}^{2+}$ Phosphor and Yellow-Emitting YAG:Ce Phosphor are proposed and investigated under different concentration of Red-Emitting $\text{Sr}_2\text{Si}_5\text{N}_8:\text{Eu}^{2+}$ Phosphor. The research results show that the color rendering index (CRI) and color quality scale (CQS) of bi-layer phosphor remote-packaging WLEDs had considerable improvement. These results provide a prospective practical solution for manufacturing bi-layered remote-packaging WLEDs. In the further works, the influence of bi-layer Red-Emitting $\text{Sr}_2\text{Si}_5\text{N}_8:\text{Eu}^{2+}$ Phosphor and Yellow-Emitting YAG:Ce Phosphor on the lighting performance of RP-WLEDs would be more developed.

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