YELLOW-EMITTING YAG:Ce PHOSPHOR: INFLUENCE OF PARTICLE SIZE ON OPTICAL EFFICIENCY OF THE HIGH COLOR TEMPERATURE CONFORMAL PACKAGING WLEDs

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In this paper, the influence of the yellow-emitting YAG:CE phosphor's particle size on the optical efficiency of high-temperature conformal packaging Multi-chip White LED (MCW-LEDs) was presented and investigated. For obtaining this goal, the physical model of the conformal packaging MCW-LEDs is simulated by using Light Tools software. Then by varying the size of the yellow-emitting YAG:CE phosphor, its influence on the correlated color temperature deviation (ΔCCT), color rending index (CRI) and lumen output of 8500 K MCW-LEDs were analyzed investigated by using Light Tools and Mat lab software. The research results showed that ΔCCT, CRI, and lumen output of 8500 K MCW-LEDs are crucially influenced by varying the size of the yellow-emitting YAG:CE phosphor. These results could be considered as a prospective approach for improving white LED manufacturer.

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Keyword: Yellow-emitting YAG:CE phosphor, ΔCCT, CRI, Lumen efficiency

1. Introduction

The operational principle of the conventional incandescent or fluorescent lamps is based on the incandescence or discharge of gases, which both are associated with significant energy losses. One of the most important events of the 1970s was the invention of the first light-emitting diodes (LEDs) by Holonyak and Bevacqua in 1962. In comparison with the conventional lamps, the operational principle of LEDs is based on spontaneous light emission in semiconductors. This principle builds on the radiative recombination of excess electrons and holes with small energy losses. LEDs have a superior lifetime, efficiency, and reliability in comparison with, which promise significant reductions in power consumption and pollution from fossil fuel power plants. Currently, LEDs are widely used in general lighting and will totally replace conventional lamps for general lighting in the near future. Commonly, three methods of creating white light in LEDs was proposed: (a)using three individual monochromatic LEDs with blue, green, and red colors; (b)combining an ultraviolet (UV)LEDs with blue, green, and red phosphors; and (c)using a blue LED to pump yellow or green and red phosphors. The last one is more commonly used in general lighting LEDs. Data from several studies suggest that the concentration and thickness of the yellow-emitting phosphor are significantly affected by the optical efficacy of Multichip White LED (MCW-LEDs). The effects of the phosphor particle size on the angular color uniformity and light extraction were proposed and investigated referring to Liu, Schubert, and Ye, respectively [1-3]. Sommer et al. found that uniform white light can be achieved by using suitable phosphor particle size depending on the targeted color temperature [4]. Smaller particle suits for higher color temperature, and giant particle suits for lower color temperature. Shi et al. showed the brightness

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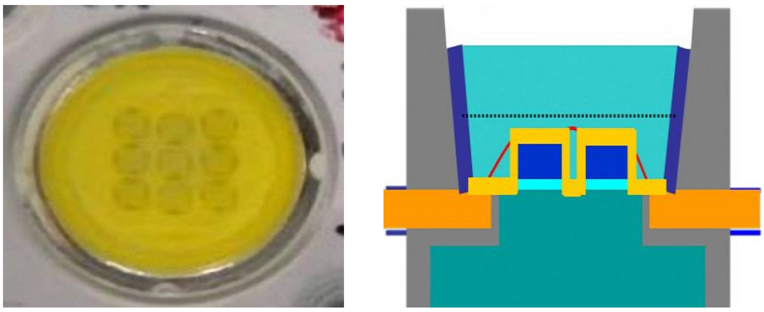
variations when the particle size varies in a wide range [5-6]. Therefore, a complete study basing on their results should be developed to understand the effects of phosphor particle size better.

Finally, this paper investigates the influence of the yellow-emitting YAG:CE phosphor particle's size on the ΔCCT, CRI and lumen output of the 8500 K MCW-LED with the conformal packaging. This paper can be organized as the followings. The first section deals with the simulation of MCW-LEDs by using Light Tools commercial software. It will then go on to calculate ΔCCT, CRI, and lumen output of MCW-LEDs while the size of the yellow-emitting phosphor changed from 1 to 7 µm. Finally, the influence of YAG:CE phosphor particles on the optical efficacy is investigated and demonstrated using Mie theory with using Mat Lab software. The investigated results showed that YAG:CE phosphor particle's size was significantly affected by ΔCCT, CRI and lumen output of MCW-LEDs.

2. MCW-LEDS physical model and theoretical description

The 8500 K conformal phosphor package MCW-LEDs was simulated using the commercial software package LightTools. The depth, the inner and outer radius of the reflector are set at 2.07 mm, 8 mm and 9.85 mm, respectively. Each blue chip has a dimension of 1.14 mm by 0.15mm, the radiant flux of 1.16 W at the peak wavelength of 453 nm. Fig. 1(a), 1(b) show that the phosphor layer is coated conformally on 9 LEDs referring to Minh [7].



a) *b)*

Fig. 1. (a) The 8500K conformal packaging MCW-LED,
(b) The schematic cross-sectional view of MCW-LEDs.

The theoretical description could be demonstrated by Mat lab software using Mie-scattering theory referring to Meneghini and Liu [8-9]. The scattering coefficient $\mu_{sca}(\lambda)$, anisotropy factor $g(\lambda)$, and reduced scattering coefficient $\delta_{sca}(\lambda)$ are calculated by expression (1), (2), and (3):

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

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

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

where $N(r)$ is the number density distribution of diffusional particles (per cubic millimeter), 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.

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

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

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 denotes the number of the unit diffusor for one diffuser concentration and K_N can be obtained by:

$$c = K_N \int M(r)dr\,. \tag{6}$$

To obtain K_N, we should first know the mass distribution *M(r)* (milligrams) of the unit diffusor. Below equation can calculate *M (r)*:

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

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

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

$$C_{sca} = \frac{2\pi}{k^2}\sum_{0}^{\infty}(2n-1)(|a_n|^2 + |b_n|^2)\,, \tag{8}$$

where *k* is the wavenumber *(2π/λ)*, 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:

$$a_n(x,m) = \frac{\psi_n^{'}(mx)\psi_n(x) - \mathrm{m}\,\psi_n(mx)\psi_n^{'}(x)}{\psi_n^{'}(mx)\xi_n(x) - \mathrm{m}\,\psi_n(mx)\xi_n^{'}(x)}\,, \tag{9}$$

$$b_n(x,m) = \frac{m\psi_n^{'}(mx)\psi_n(x) - \psi_n(mx)\psi_n^{'}(x)}{m\psi_n^{'}(mx)\xi_n(x) - \psi_n(mx)\xi_n^{'}(x)}\,, \tag{10}$$

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 according to the following equation) [10-12]

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

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

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

$$S_1 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \begin{bmatrix} a_n(x,m)\pi_n(\cos\theta) \\ +b_n(x,m)\tau_n(\cos\theta) \end{bmatrix}, \tag{13}$$

$$S_2 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \begin{bmatrix} a_n(x,m)\tau_n(\cos\theta) \\ +b_n(x,m)\pi_n(\cos\theta) \end{bmatrix}. \tag{14}$$

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. [14-21]

Here, Mie-scattering theory [8-9] could be applied to derive the relationship of luminous output to the Y2O3:Eu3+ weight rigorously.The transmitted light power can be calculated by the Lambert-Beer law. [12-15]

$$I = I_0 exp(-\mu_{ext} L) \tag{15}$$

where I is the transmitted light power, I_0 is the incident light power, $\mu_{ext} = N.C_{ext}$ is the extinction coefficient, L is the path length, N is the number of particles per cubic millimeter.

According to Mie-scattering theory, the extinction cross section C_{ext} of phosphor particles can be characterized by the following equation:

$$C_{ext} = \frac{2\pi a^2}{x^2} \sum_{n=1}^{\infty} (2n+1)\,\mathrm{Re}(a_n + b_n) \tag{16}$$

where $x = 2\pi a/\lambda$ is the size parameter, a_n and b_n are the expansion coefficients with even symmetry and odd symmetry, respectively.

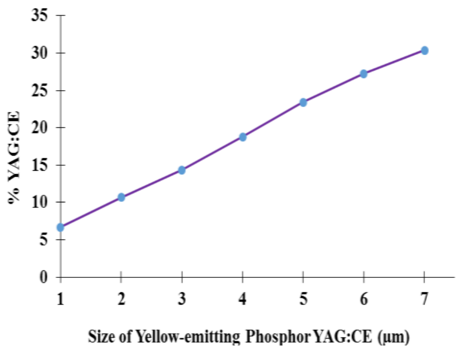


Fig. 2. Size and concentration YAG:CE particle of 8500 K conformal packaging MCW-LEDs.

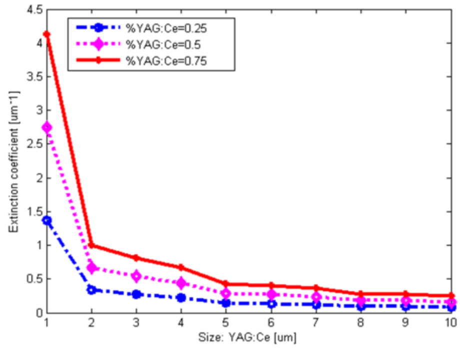


Fig. 3. Extinction coefficient of YAG:CE particle of MCW-LEDs 8500 K.

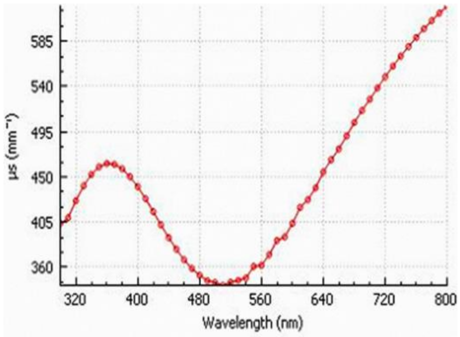


Fig. 4. Particle size distribution is approximated by lognormal functions of YAG:CE particle of MCW-LEDs 8500 K.

3. Result and discussion

In this research, ΔCCT, CRI and lumen output of the conformal package MCW-LEDs for various sizes of YAG:CE particle from 1 µm to 7 µm were calculated, compared and analyzed. Firstly, the size and concentration YAG:CE were displayed in Fig. 2. In the phosphor compounding, the concentration of the yellow-emitting phosphor increased with increasing the size of the phosphor's particle. Fig. 5 displayed the calculated ΔCCT of MCW-LEDs 8500K. On Figures 6 and 7 the CRI and lumen output was displayed. From simulation results, ΔCCT of MCW-LEDs 8500K decreased from 3700 to 2300 while the size YAG:CE phosphor increased from 1 µm to 7 µm (Fig. 5). Moreover, the optimal value of the particle's size is around 5-7 µm. On another hand, CRI obtained maximum value near 75 with size YAG:CE phosphor from 2 µm to 3 µm (Fig. 6). However, lumen output significantly increased with size YAG:CE phosphor increased from 1 µm to 4 µm and then slightly decreased. Finally, the results show that that size YAG:CE phosphor was influenced by ΔCCT, CRI and lumen output of the conformal package MCW-LEDs.

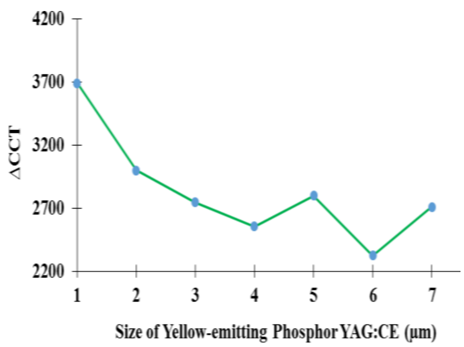


Fig. 5. The ΔCCT of the conformal packaging 8500 K MCW-LEDs with different YAG:CE particle size.

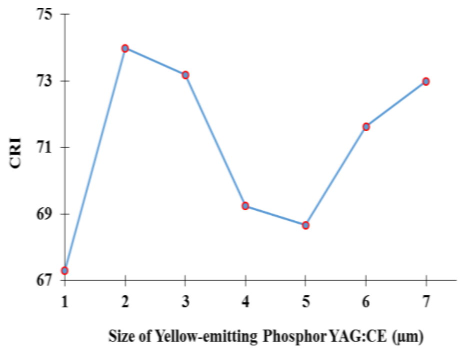


Fig. 6. The CRI of the conformal packaging 8500 K MCW-LEDs with different YAG:CE particle size.

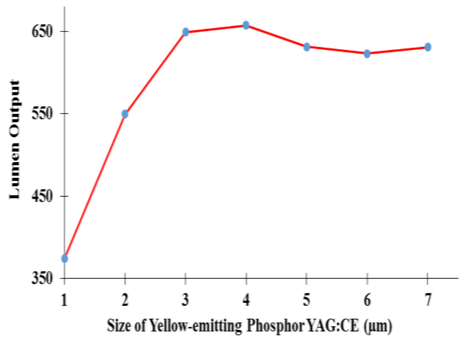


Fig. 7. The lumen output of the 8500 K conformal packaging MCW-LEDs with different YAG:CE particle size.

4. Conclusions

In the paper, the effect of the yellow-emitting YAG:CE phosphor particle's size on ΔCCT, CRI, and lumen output of the 8500K conformal packaging MCW-LEDs was proposed, analyzed and demonstrated. Furthermore, some conclusions are proposed: 1) ΔCCT notably decreased, and CRI significantly increased in continuously increasing the size of the yellow-emitting YAG:CE phosphor particle; 2)CRI can be obtained near 80 with the 8500K conformal packaging MCW-LEDs; 3) lumen output notably increased with continuously increasing size of the yellow-emitting YAG:CE phosphor particle. Finally, the results provided a considerable approach to improving optical properties of MCW-LEDs with high CCT.

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