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Effect of YAG:Ce Particle Size on Lighting Performance of High Color Temperature Multi-chip White LED

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Abstract

In recent year, main research direction in LED technology is improving lighting performance of white LED (CRI and lumen output). In this paper, effect of YAG:CE particle size on lighting performance of Multi-chip White LED (MCW-LEDs) is considered like an innovative method for improving their lighting performance. Main approaches of this work are: 1) using MCW-LEDs with high color temperature (CCT) near 8500 K, 2) investigating and demonstrating the effect of YAG:CE particle size on lighting performance of Multi-chip White LED with CCT 8500 K. Firstly, the phosphor layer mechanism of real MCW-LEDs with flat silicone coating is simulated by using LightTools 8.1.0 program. Then by varying YAG:CE particle size, ΔCCT, CRI and lumen output of MCW-LEDs were calculated and analyzed. The simulation and experimental results showed that ΔCCT, CRI and lumen output of MCW-LEDs of 8500 K MCW-LEDs are significantly influenced by varying YAG:CE particle size. These results can be a prospective ideal for future improving white LED manufacture.

Keywords: *YAG:CE particle size, CRI; lumen output; multi-chip white LEDs, high color temperature*

1. Introduction

In recent years, remarkable efforts have been developed to MCW-LEDs, which have regarded as the promising illumination method to replace the traditional lighting sources due to their superior features, such as low power consumption, high efficiency, long life and variable color (Yu, Chung and Kim 2010, Hung and Tsao 2013). Consequently, MCW-LEDs have been developed actively and require a high CRI (>78) and lumen output for lighting applications (Lohaus *et al.*, 2013 and Oh *et al.*, 2015). The conventional MCW-LED involves a combination of nine blue LEDs with the yellow YAG:Ce phosphor compounding as shown in Figure 1. However, this system has a poor color rendering ability (<74) due to the lack of red components in the spectrum. Recently, to increase CRI close to 90 at CCT <3000 K, the quantum dot nanophoshor and the warm-white LEDs are combined (Nizamoglu *et al.*, 2011). Li *et al.*, (2013) proposed pulse-sprayed conformal phosphor configuration for LEDs having CCT from 2700 K to 4700 K, resulting in reaching a CRI value as high as 85.6. Besides, Chen and Hui (2015) have been offered a new research and development tool for practical LED system designers to predict the

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instantaneous variations of CCT and CRI when the power varies in an LED system. Indeed, the mentioned studies also proposed the methods to improve lumen output and CRI. However, their obtained results are at a low level for illumination applications. Moreover, the studies only focus on single-chip white LED lamps. These lamps have little relation to multi-chip white LED lamps having higher CCTs (>7500 K) (Schratz *et al.*, 2011, Peng, Hwang and Devarajan 2014). Thus, how to maintain the balance of the CRI and the good lumen output are the crucial point in MCW-LED packages, and should be addressed rigorously.

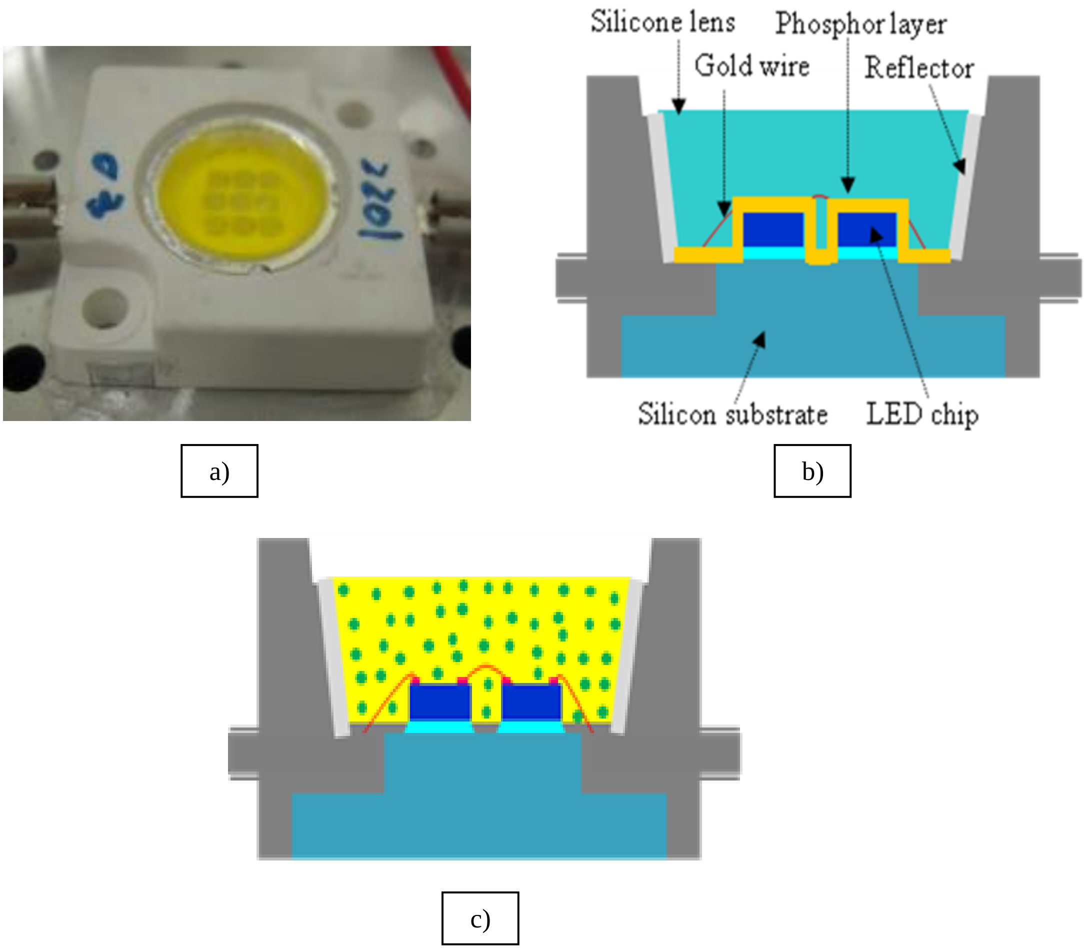

Figure 1. (a) The Actual MCW-LED with Conformal Phosphor Layer, (b) Its Schematic Cross-Sectional View, (c) The Simulated In-Cup Phosphor Packaging (CPP)

In this paper, effect of YAG:CE phosphor particle's size in the phosphor compounding of MCW-LEDs on their ΔCCT, CRI and lumen output is proposed, investigated and analyzed. We demonstrate that YAG:CE phosphor particles size can effect on lighting performance of MCW-LEDs. This work can divide into 3 steps: 1) Simulation of MCW-LEDs by using LightTools 8.1.0 program; 2) Varying YAG:CE particle size in the phosphor compounding of MCW-LEDs and calculating ΔCCT, CRI and lumen output of MCW-LEDs; 3) Analyzing and investigating the effects of YAG:CE phosphor particles size in the phosphor compounding of MCW-LEDs on their ΔCCT, CRI and lumen output. The investigated results show that YAG:CE phosphor particle's size was significally affected on ΔCCT, CRI and lumen output of MCW-LEDs.

2. Main Part

2.1. MCW-LEDs Physical Model

The simulations were carried out using the commercial software package LightTools. The simulation comprised the setup of the conformal phosphor package (CPP) with average CCT of 8500 K. Firstly, to guarantee that our simulation results reflect precisely the impact of our considered parameters and are not biased by other factors such as LED's wavelength, waveform, light intensity, and operating temperature, we use the real-world model of MCW-LEDs. This model possesses the best optical-thermal stability, hence, can minimize the variations caused by uninterested parameters. Secondly, to make the comparison fair, the same silicone lens and structures are used for CPP and IPP. Specifically, we set the depth, inner and outer radius of reflector to 2.07 mm, 8 mm and 9.85 mm, respectively. Nine LED chips are covered by either CPP or IPP, which respectively have fixed thickness of 0.08 mm and 2.07 mm. Each blue chip has a dimension of 1.14 mm by 0.15mm, the radiant flux of 1.16 W, and the peak wavelength of 453 nm (Figure 1(a), 1(b)). Figure 1(c) shows that the phosphor layer of CPP is coated conformally on 9 LEDs.

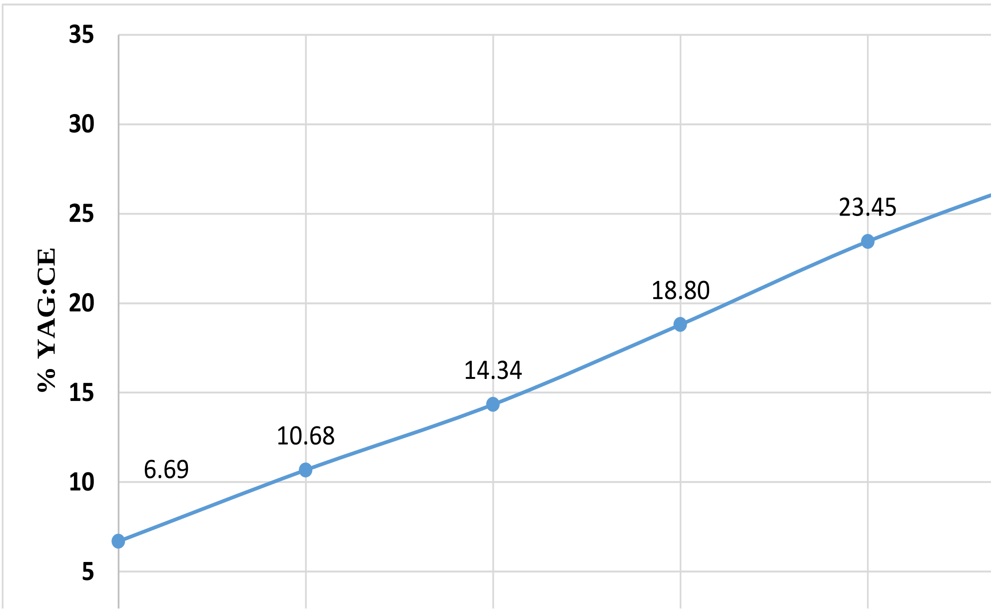

Figure 2. Size and Concentration YAG:CE Particle of MCW-LEDs 8500 K

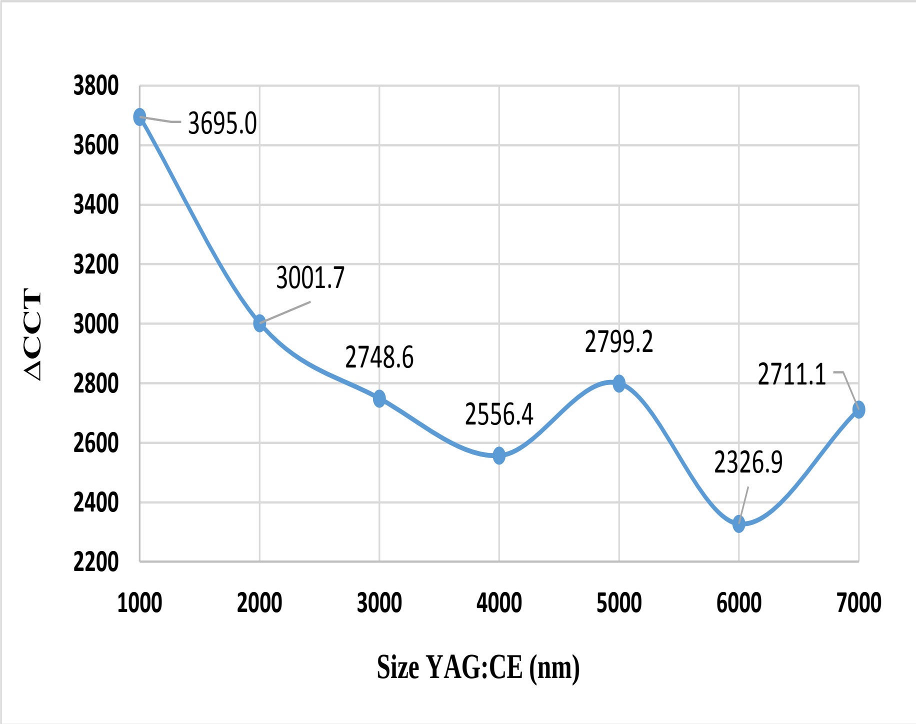

Figure 3. The △CCT of MCW-LEDs 8500 K with Different YAG:CE Particle Size

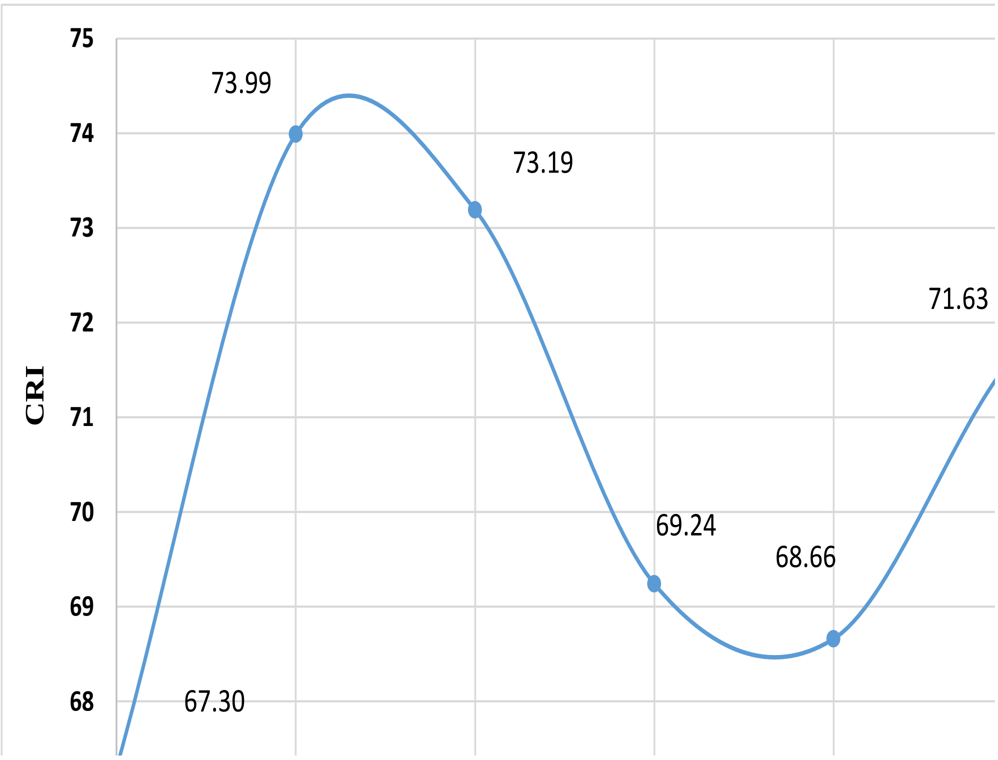

Figure 4. The CRI of MCW-LEDs 8500 K with Different YAG:CE Particle Size

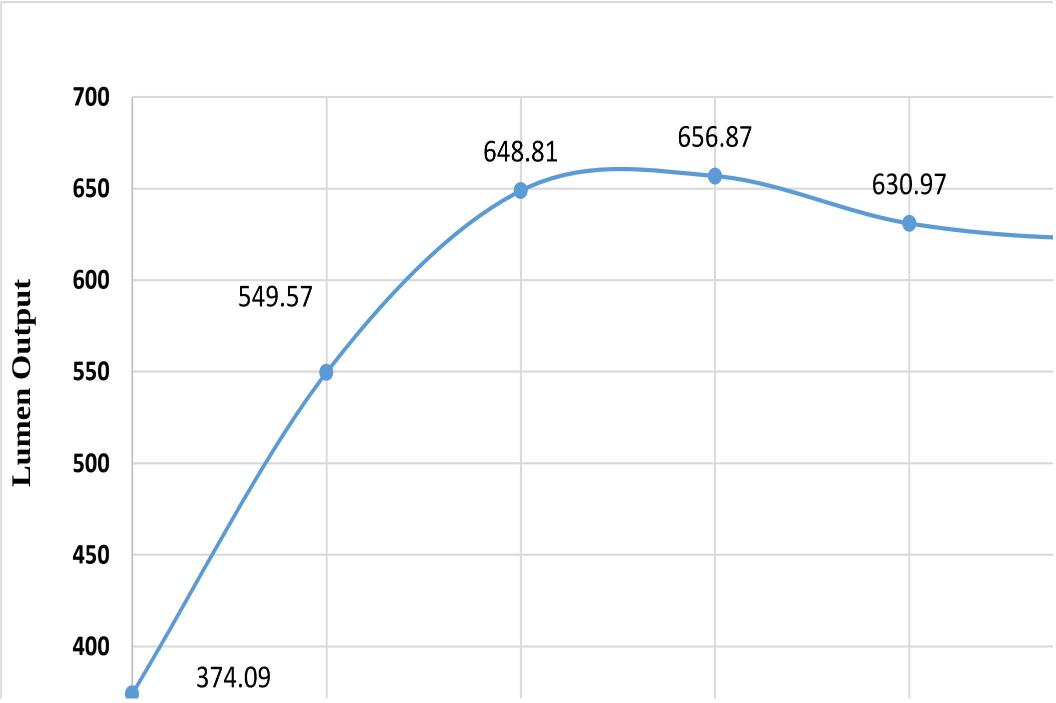

Figure 5. The Lumen Output at Average CCT 8500 K with Different YAG:CE Particle Size

2.2. Simulation Results and Discussions

In this work, 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 on Figure 2. Figure 3 displayed the calculated ΔCCT of MCW-LEDs 8500K. On Fig. 4 and 5 the CRI and lumen output were calculated and displayed respectively. 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 (Figure 1). On another hand, CRI obtained maximum value near 75 with size YAG:CE phosphor from 2 µm to 3 µm (figure 2). However, lumen output significally increased with size YAG:CE phosphor increased from 1 µm to 4 µm and then slightly decreased. Finally, we can demonstrate that size YAG:CE phosphor was influenced on ΔCCT, CRI and lumen output of the conformal package MCW-LEDs.

Here, we can apply Mie-scattering theory (Liu and Luo 2011) 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 (Shuai *et al.*, 2012):

$$I = I_0 exp(-\mu_{ext} L) \quad (1)$$

where I is the transmitted light power,

I0 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:

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

where x = 2πa/λ is the size parameter,

a_n and b_n are the expansion coefficients with even symmetry and odd symmetry, respectively.

The parameters a_n and b_n are defined as:

$$a_n(x,m) = \frac{\psi_n'(mx)\psi_n(x) - m\psi_n(mx)\psi_n'(x)}{\psi_n'(mx)\xi_n(x) - m\psi_n(mx)\xi_n'(x)} \quad (3)$$

$$b_n(x,m) = \frac{m\psi_n'(mx)\psi_n(x) - \psi_n(mx)\psi_n'(x)}{m\psi_n'(mx)\xi_n(x) - \psi_n(mx)\xi_n'(x)} \quad (4)$$

where a is the spherical particle radius,

λ is the relative scattering wavelength,

m is the refractive index of scattering particles,

$\psi_n(x)$ and $\xi_n(x)$ are the Riccati-Bessel functions.

3. Conclusion

In the paper, the effect of YAG:CE phosphor size on ΔCCT, CRI and lumen output of MCW-LEDs with high CCT 8500 K was analyzed and demonstrated. Some conclusions are proposed: 1) ΔCCT significantly decreased, and CRI increased with continuously increasing size of YAG:CE phosphor; 2) CRI can be obtained near 80 with MCW-LEDs 8500 K; 3) lumen output notably increased with continuously increasing size of YAG:CE phosphor. Results have a huge value in improvement lighting performance of MCW-LEDs with high CCT.

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