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Regulating the white LED properties with different SiO_2 particle sizes

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The scattering factor plays a pivotal role in enhancing the optical performance of white light-emitting diodes (LEDs). This paper presents a simulation study in which SiO_2 nanoparticles are employed to harness their scattering enhancement effects in blue-pumped white LEDs. The scattering functions of the particles are simulated and computed using the Mie scattering theory. Throughout the study, the concentrations of SiO_2 and phosphor-film thickness are kept constant, while the size of SiO_2 particles is systematically varied to investigate its impact on the lighting performance of the white LED. We comprehensively assess and discuss the lumen output and chromatic performance of the LED under different SiO_2 particle size scenarios. Our findings reveal that by increasing the SiO_2 particle size, significant improvements can be achieved in specific properties of the white LED, providing valuable insights for optimizing LED design and performance.

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Keywords: White LED, Scattering properties, Color rendering index, Luminous efficacy

1. Introduction

The blue-pumped white LED is a promising light source for illumination and display applications, due to its low-energy consumption, high light efficiency and long lifetime [1, 2]. However, the conventional white LED, which uses a blue-emitting GaN chip and a yellow phosphor YAG:Ce^{3+}, suffers from low luminous efficiency, low CRI, and low color reproducibility. Therefore, there is a need to improve the performance of the white LED by using different phosphors and encapsulation materials [3-5].

One of the approaches to enhance the efficiency of the white LED is to use green/red phosphors, which have high emission intensity and stability [6-8]. However, these phosphors have the drawback of absorbing the blue and green emission from the other phosphors, which reduces the color quality of the white LED. Another approach is to incorporate nanoparticles in the silicone encapsulant, which can increase the light extraction and scattering of the white LED. Adding ZrO_2 nanoparticles to the remote phosphor structure improved the luminous efficacy of the white LED. In another paper, a TiO_2@silicone layer was applied to redirect the backscattered blue light from the chip-on-board packaging LEDs [9-11]. It also demonstrated that the light extraction decreased with increasing phosphor concentration, indicating that the scattering effect of the phosphor was stronger than that of the nanoparticles [12, 13].

SiO_2 nanoparticles are widely used in various fields such as biotechnology, food preservation, agriculture, and medicine, because of their low-cost, hydrophilic, biocompatible, porous, and tunable properties [14]. In lighting fields, SiO_2 nanoparticles have been applied to improve the performance of different types of LEDs, such as blue-pumped LED [15], quantum-dot LED [16], and ultraviolet-pumped LED [7]. These studies showed that varying the concentration of SiO_2 nanoparticles can affect the efficiency of the LEDs. However, there is a lack of research on how changing the size of SiO_2 nanoparticles can influence the optical properties of the LEDs.

This paper explores the use of SiO_2 nanoparticles in simulating the performance of the blue-pumped white LED to exploit their scattering enhancement effects. The concentration of the phosphor and SiO_2 remains constant, while the size of the SiO_2 particles is modified to assess the lighting performance of the white LED. The study investigates and discusses the LED's lumen output and chromatic performance. Results demonstrate that by adjusting the particle size of SiO_2, specific properties of the white LED can be improved.

2. Scattering computation

To understand the scattering influence of nanoparticles SiO_2 in the package we utilized the Mie-scattering theory to make a scattering computation with MATLAB [18-20]. The scattering coefficient $\mu_{sca}(\lambda)$ and reduced scattering coefficient $\delta_{sca}(\lambda)$ are calculated using the following formulas:

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

$$\delta_{sca} = \mu_{sca}(1-g) \tag{2}$$

where N(r) denotes the distribution density of particles in phosphor layer (mm^3), which is comprised of the density of SiO_2 particles $N_d(r)$ and phosphor granules $N_p(r)$. C_{sca} represents the scattering cross sections (mm^2), obtained using equation (3). g is the anisotropy factor. λ and r indicate the light wavelength (nm) and particle size of SiO_2 (μm), respectively.

$$C_{sca} = \frac{2\pi}{k^2}\sum_{0}^{\infty}(2n-1)(|a_n|^2 + |b_n|^2) \tag{3}$$

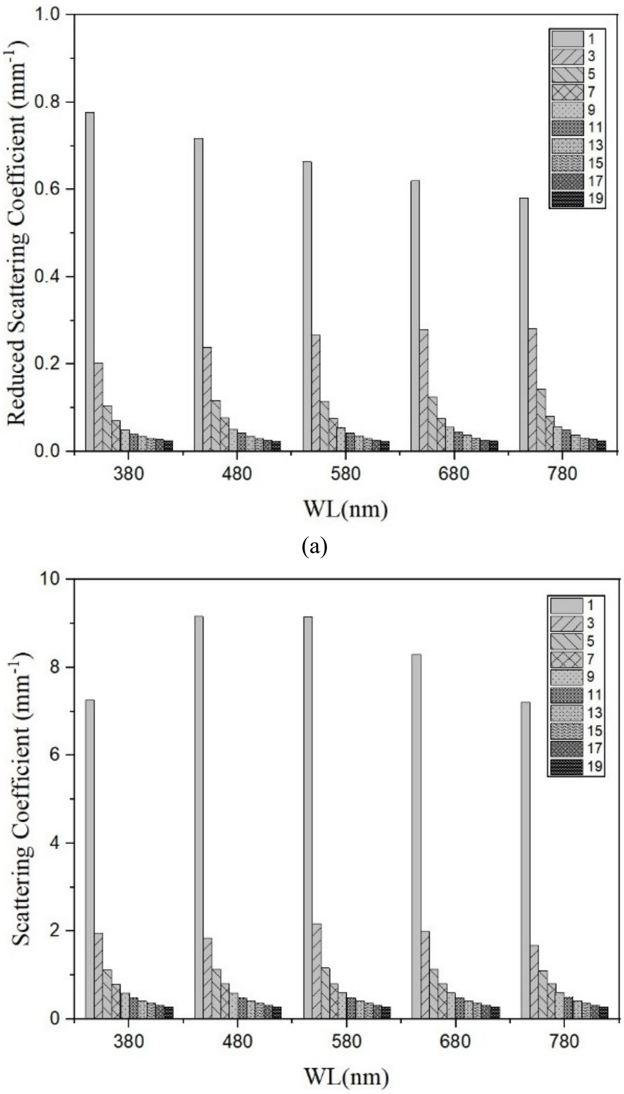
where $k = 2\pi/\lambda$; a_n and b_n represent expansion coefficients with even symmetry and odd symmetry, respectively, obtained using equations 4 and 5:

$$a_n(x,m) = \frac{\psi_n^{'}(mx)\psi_n(x) - \mathrm{m}\psi_n(mx)\psi_n^{'}(x)}{\psi_n^{'}(mx)\xi_n(x) - \mathrm{m}\psi_n(mx)\xi_n^{'}(x)} \tag{4}$$

$$b_n(x,m) = \frac{m\psi_n^{'}(mx)\psi_n(x) - \psi_n(mx)\psi_n^{'}(x)}{m\psi_n^{'}(mx)\xi_n(x) - \psi_n(mx)\xi_n^{'}(x)} \tag{5}$$

with $x = k.r$, m denotes the refractive indices, $\psi_n(x)$ and $\xi_n(x)$ represent Riccati - Bessel functions.

The $\mu_{sca}(\lambda)$ scattering coefficients and $\delta_{sca}(\lambda)$ reduced scattering coefficients are displayed in Fig. 1. The SiO_2 particle size ranges from 1 μm - 19 μm. The wavelength range is 380-780 nm. Both graphs in Fig. 1 show that the larger the radius of the SiO_2 particle, the lower the scattering values. This means to increase the scattering factors, using small SiO_2 at adequate particle sizes is essential. Besides, the scattering factors fluctuate between wavelengths (shortened as WL in all figures). In Fig. 1(a), when the particle size is less than 2 μm, the $\delta_{sca}(\lambda)$ shows the highest values under the 380 nm wavelength (ultraviolet) while decreasing under longer wavelengths (visible to near-infrared). Meanwhile, with larger particle sizes (from 3 μm to above), the $\delta_{sca}(\lambda)$ is the lowest under 380 nm wavelength while gradually increasing as the wavelength becomes longer. This implies that the scattering at the random walk within the medium is better in the visible-to-near-infrared light range than the ultraviolet one, making the SiO_2 medium appropriate for visible and near-infrared lighting and imaging applications. Meanwhile, the $\mu_{sca}(\lambda)$ in Fig. 1(b) increases and reaches its peak at wavelengths of 480 nm and 580 nm, then begins to decrease with longer wavelengths. These results indicate that the scattering of visible light is higher than that of other wavelengths. This suggests that SiO_2 particles are well-suited as a scattering agent in the phosphor film to enhance scattering at the surface between spherical granules in the layer, resulting in light being scattered in all directions for better uniformity of light output.



(a)

(b)

Fig. 1. Scattering properties with different SiO_2 radii: (a) reduced scattering coefficients and (b) scattering coefficients

3. Results and discussion

The change of the particle size of the scattering particle SiO_2 (as denoted as GEP in all figures hereafter) also influences the YAG:Ce doping concentration. The lowest YAG:Ce amount is observed when the SiO_2 particle size is at 1 μm, as shown in Fig. 2. With larger particle size of SiO_2, the concentration of YAG:Ce increases and fluctuates in a small range. The YAG:Ce concentration peak is collected at more than 27.4% with a SiO_2 radius of 5 μm, increasing by 1.8% compared to the concentration with 1-μm SiO_2. The lower YAG:Ce amount can reduce the phosphor particle density in the layer, increasing the interaction between the light and SiO_2 nanoparticles, and inducing the scattering factors as a result. However, this could reduce the light emitting intensity of the LED owing to the insufficient absorption and conversion of the phosphor with low particle density in the layer.

Paradoxically, as depicted in Fig. 2, it is important to note that increasing the phosphor weight concentrations in LEDs as the SiO_2 particle sizes grow larger is essential. Although larger particles can exhibit greater emission intensity due to better forward scattering, the necessity for larger phosphor amounts remains imperative to achieve white LEDs. This phenomenon is contingent upon the quantity of phosphor particles integrated into the LEDs. During production, all white LEDs were uniformly assembled with phosphor layers of identical thickness. Subsequently, the number of particles was calculated for each phosphor fraction. It was determined that emitting sufficient yellow light to generate white light requires a greater quantity of smaller particles to partake in the luminescent process. Furthermore, the reduction in particle size is linked to decreased absorption, emission, and excitation characteristics, necessitating a compensatory increase in the number of particles.

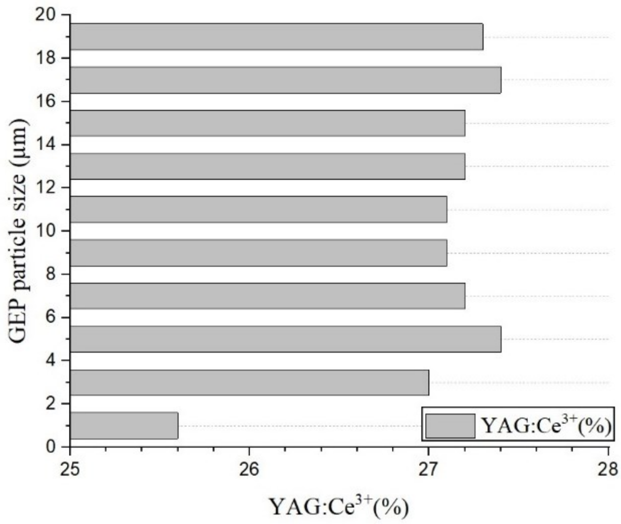


Fig. 2. YAG:Ce concentration levels with different SiO_2 radii

The emission intensity and lumen output of the LED-generated white light are subsequently depicted in Figs. 3 and 4, respectively. The data from the two graphs confirms that increasing the SiO_2 particle size can achieve improved emission strength and lumen for the LED. The recorded emission band shows two peaks at ~450 nm and 575 nm, originating from the blue LED chip and the yellow phosphor. The highest intensities in those peaks and the lumen output of the LED are obtained with 9 μm of SiO_2 particle size. As the light traverses through the particles, the scattering characteristics exert a pronounced influence on LED emission. Larger particle sizes manifest a scattering pattern that predominantly directs emission forward. Conversely, smaller particle sizes result in omnidirectional light scattering, causing a portion of the emission to be backscattered and subsequently absorbed by the LED chip. This phenomenon significantly contributes to the reduction in LED efficiency when employing SiO_2 particles of smaller size.

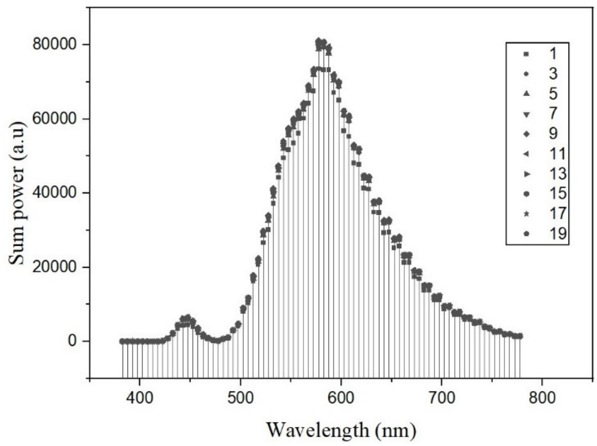


Fig. 3. Total emission of the white LED with different SiO_2 radii

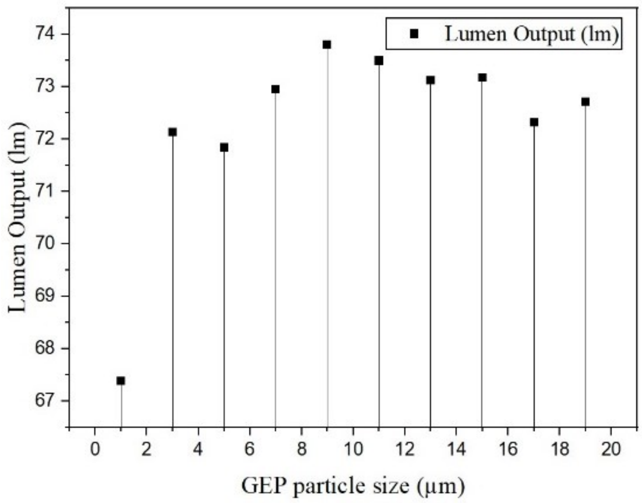


Fig. 4. Lumen output of the white LED with different SiO_2 radii

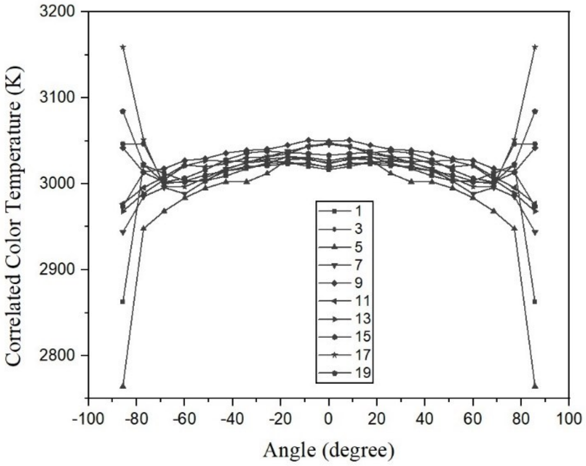
When the scattering factor is stimulated, it facilitates an enhanced transformation of light color. This, in turn, can mitigate the undesirable yellow-ring effect and promote greater uniformity in the resulting white light. A reduction in particle size can yield improved color quality, primarily due to the broader scattering angle associated with larger particles, which results in a more frequent mixing of light rays. However, it is essential to recognize that this heightened mixing process diminishes the energy output, consequently diminishing the brightness of the LED. The chromatic distribution uniformity is assessed using the angular correlated color temperature (CCT) data supported by the delta-CCT level [21], demonstrated in Fig. 5. The primary factor responsible for the non-uniform distribution of chromaticity, often referred to as delta-CCT or the deviation between CCT ranges, is closely associated with light emission angles. For a comprehensive assessment of the light quality offered by pc-LEDs, it is imperative to take into account the disparities in CCT across different emission angles. To quantify the angular CCT deviation, we can employ the subsequent equation:

$$\Delta CCT = CCT_{(Max)} - CCT_{(Min)} \tag{6}$$

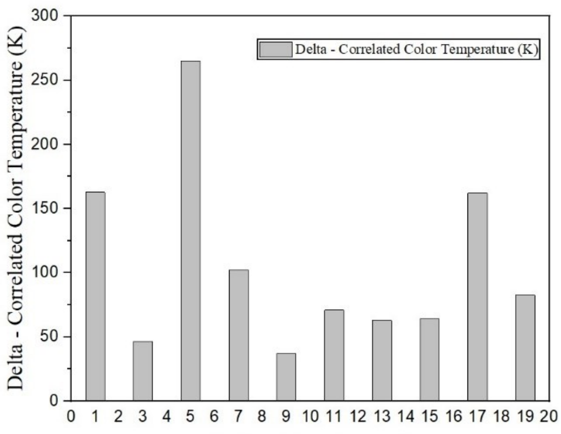
where $CCT_{(Max)}$ and $CCT_{(Min)}$ represent the CCT values at 0° and at 90° viewing angles, respectively.

The angular CCT in Fig. 5(a) decreases with increasing size of SiO_2 particles, in general. The largest and smallest CCT ranges are noted when particle sizes of SiO_2 are 5 µm and 9 µm, respectively, confirmed with data in Fig. 5(b). The lower the delta-CCT level, the higher the chroma uniformity. Thus, the optimal particle size of SiO_2 to obtain the best chroma-distribution uniformity is about 9 µm.

The chroma rendering index (CRI) and chroma quality scale (CQS) [22, 23] in Fig. 6 are used to assess the color reproduction performance of the white LED light. Compared with the smallest SiO_2 particle size, the larger particles contribute to increasing the rendition parameters, as seen in both Fig. 6(a) and 6(b). There is a notable fluctuation, but the increase can be interpreted in general. Moreover, the fluctuation in CQS is less intense than that in the CRI levels [24, 25]. The peaks of CRI and CQS are obtained when the SiO_2 particle size of 9 µm is utilized. Henceforth, based on the results, 9 µm is the optimal size for SiO_2 particles in the phosphor layer to accomplish the improvement in both luminosity and chroma distribution and rendition properties.

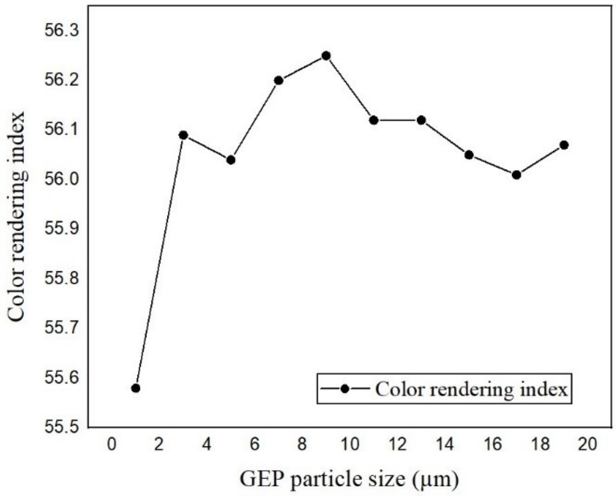


(a)

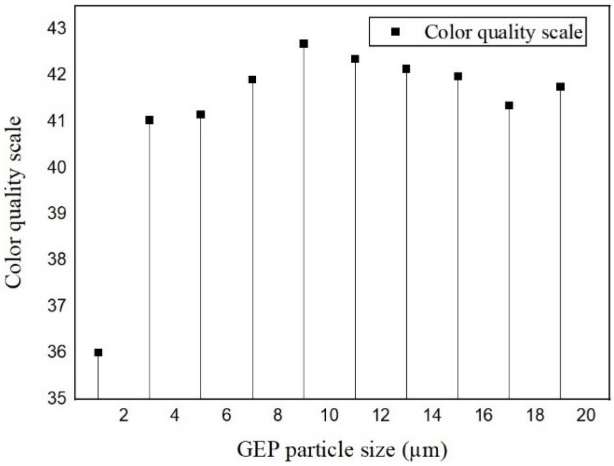


(b)

Fig. 5. The chromatic uniformity with different SiO_2 radii: (a) angular CCT ranges and (b) delta CCT levels



(a)



(b)

Fig. 6. Chromatic reproduction performance with different SiO_2 radii: (a) chromatic rendering index and (b) chromatic quality scale

4. Conclusions

The paper presents a study focusing on the simulation of white LED lighting with the utilization of SiO_2 nanoparticles to enhance scattering effects. The research indicates that the incorporation of small SiO_2 particles contributes to an improvement in the LED package's scattering performance. However, it is noted that excessively small SiO_2 particles may diminish the lighting efficiency of the white LED due to reduced absorption and conversion efficiency, along with the loss of light energy caused by backscattering. This leads to a more omnidirectional scattering of light rather than predominantly forward. The findings demonstrate that increasing the size of the SiO_2 particles results in enhanced luminosity and color quality of the white LED, surpassing the performance achieved with 1-µm SiO_2 particles. According to the study, the optimal radius for SiO_2 particles is determined to be 9 µm, as this size enables the attainment of peak luminosity, the most uniform chromaticity distribution, and the best color production performance.

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