ORIGINAL ARTICLE

Color and Illuminance Uniformity Enhancement of Multi-chip White LEDs by Complementing Silica Particles

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Abstract: We analyze the influence of silica particle (SiO_2) concentrations on color and illuminance uniformity of multi-chip white LEDs (MCW-LEDs) with a correlated color temperature (CCT) near 7700 K. It is suggested that the novel phosphor silicone layer (PSL), which added silica particles, can improve CCT and illumination uniformity. Using the commercial simulation program LightTools, based on Monte Carlo method, the novel PSL demonstrated a reduction of the CCT deviation (DCCT) to 1719 K from 2211 K, while the illuminance uniformity increased from 0.328 to 0.353. The simulation results could be totally convinced by Mie theory. This results point towards an approach for manufacturing high-quality MCW-LEDs.

Keywords: Multi-chip white light LEDs (MCW-LEDs), SiO_2, quartz, color uniformity, illuminance

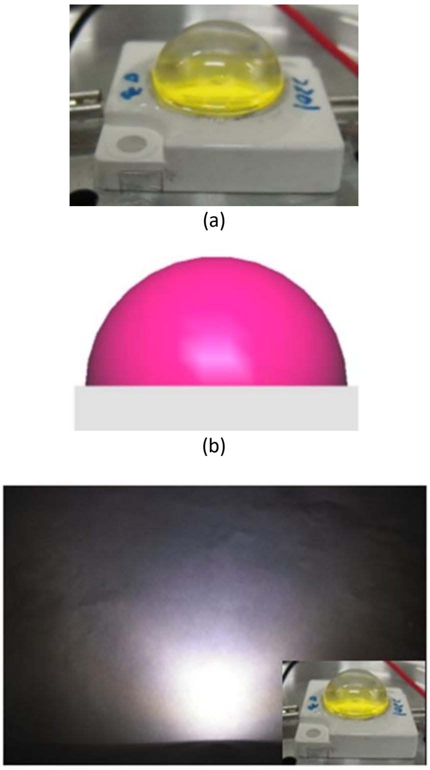
Introduction

Over the last few decades, white light-emitting diodes (LEDs) have been emerged as a next -generation light source due to low cost, small size, environmentally friendliness, long lifespan, compactness, and high luminous efficiency [1-3]. Angular color uniformity (ACU) and illuminance uniformity (IU) are generally the main optical properties considered in LED design to improve light extraction. MCW-LEDs offer advantages in terms of efficiency, compactness, stability and lifespan, prompting the rapid development of the phosphor silicone layer (PSL) to obtain further quality improvements. Many methods have been proposed to improve the ACU, particularly through changes to the PSL structure of white light LED packaging, while IU is optimized through improvements to MCW-LEDs package components, such as Fresnel lenses, LED arrays and patterned reflectors [4-8].

The conventional PSL of the popular white light LEDs structures contains phosphor YAG:Ce particles and silicone glue uniformly. PSL absorbs the excited blue light from the chips to generate yellow light, thus producing white light.

Due to the difference in the radiant intensity distribution of the phosphor-scattered blue light and the phosphor-emitted yellow light, the spatial color distribution of white light LEDs is non-uniform. A non-optimized LEDs package can produce unexpected results such as the appearance of a yellow ring in our MCW-LEDs product (Fig.1). During the multi-scattering process, the blue light is weakened due to phosphor absorption, but the converted yellow light increases due to further scattering. Therefore, the final ACU of white LEDs significantly depends on the scattering effects of PSL, and increased PSL scattering thus enhances white light uniformity [9].

The size, thickness, concentration and the refractive index of the phosphor are important factors for adjusting the scattering of PSL. For that reason, white light quality is also improved over time [10-13]. This paper uses silica particles SiO_2 in the PSL of MCW-LEDs to improve color uniformity and illumination. First, an optical and a simulation model of MCW-LEDs are created commercial using LightTools software based on the Monte Carlo method. The scattering effect of silica particles SiO_2 is then analyzed and demonstrated using MATLAB software based on Mie theory. Finally, we conduct spatial color distribution analysis and verify illumination uniformity. The results clearly show that the silica particle dominates the light scattering process in the PSL to improve uniformity of spatial color and illumination distribution. This research provides a prospective solution for the production of high quantity MCW-LEDs.


(a)

(b)

(c)

Figure 1. (a) Real physical model of MCW-LEDs; (b) Simulation model of MCW-LEDs; (c) Yellow ring in the experimental MCW-LEDs.

PHU Tran Tin was born in Khanh Hoa, Viet Nam, in 1979. He received the Bachelor degree (2002) and Master degree (2008) from Ho Chi Minh City University of Science. In 2007, he was lecturer at the Faculty of Electronics Technology (FET), Industrial University of Ho Chi Minh City. Since 2015, he has been participating in Ph.D program, that had been linked between Technical University of Ostrava, Czech Republic and Ton Duc Thang University, Ho Chi Minh City. His major research interests are wireless communication in 5G, energy harvesting, performance of cognitive radio, physical layer security, and optoelectronics.

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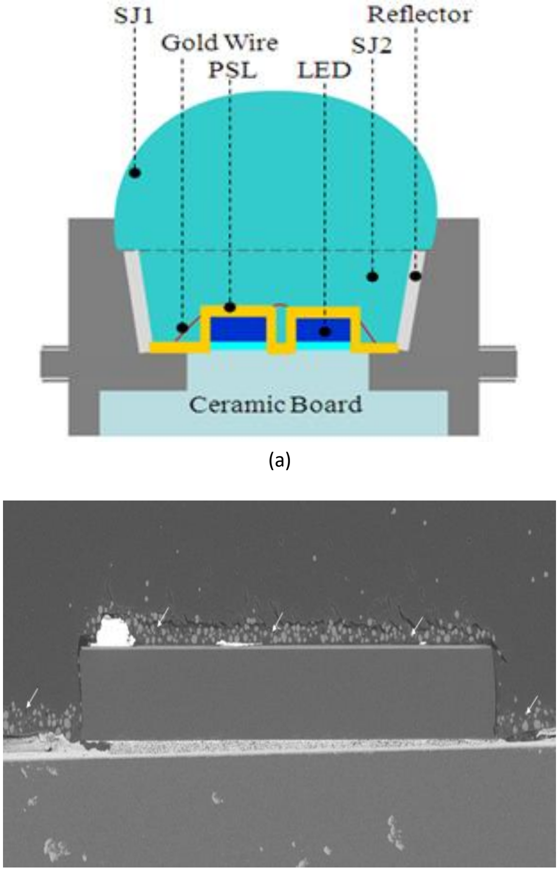
Optical and Simulation Model

We use LightTools software based on the Monte Carlo method to simulate the PSL structure of the MCW-LEDs. A ray tracing simulation uses a thin PSL with a fixed thickness of 0.08 mm. The silicone lens are SJ_1 and SJ_2, cover 9 LED chips and are adhered to the board. SJ_1 and SJ_2 have respective refractive indexes of 1.41 and 1.53, while the radius of SJ_1 is 6mm and the height of SJ_2 is 2mm. Each LED chip has a square base of 1.14 mm and a height of 0.15 mm, and is bound to the center of the board.

Defining the optical properties of the MCW-LEDs model and its PSL is of essential importance [11-13]. Varying the silica concentration would alter the ACU and IU optical performance due to enhanced scattering in the proposed PSL.

The proposed PSL structure adds silica particles to the conventional PSL (Fig. 2). The refractive index of silica particles, phosphor particles, and silicone matrix are respectively 1.54, 1.83 and 1.52, as in the actual material. The silica and phosphor particles respectively have radii of 1 μm and 7.25 μm. The blue chip MCW-LEDs have a flux of 1.16 W at a wavelength of 453 nm (Fig. 3).



(a)

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Figure 2. (a) Schematic illustration of the optical structure of the actual MCW-LED and (b) SEM images of cross section of PLS structure.

The intensity distribution of blue and yellow light is obtained through applying simulation software to conventional PSL. These data can be used to obtain yellow-blue ratio curves of the MCW-LEDs that vary with different angles. The results in Fig. 4 show that the conventional PSL structure has a serious deviation ratio. On the other hand, the proposed PSL structure can maintain a higher ratio consistency from 0 to 180 degrees. From that point, the geometric color mixing effect of the conventional PSL structure declines in comparison to that of the proposed PSL structure.

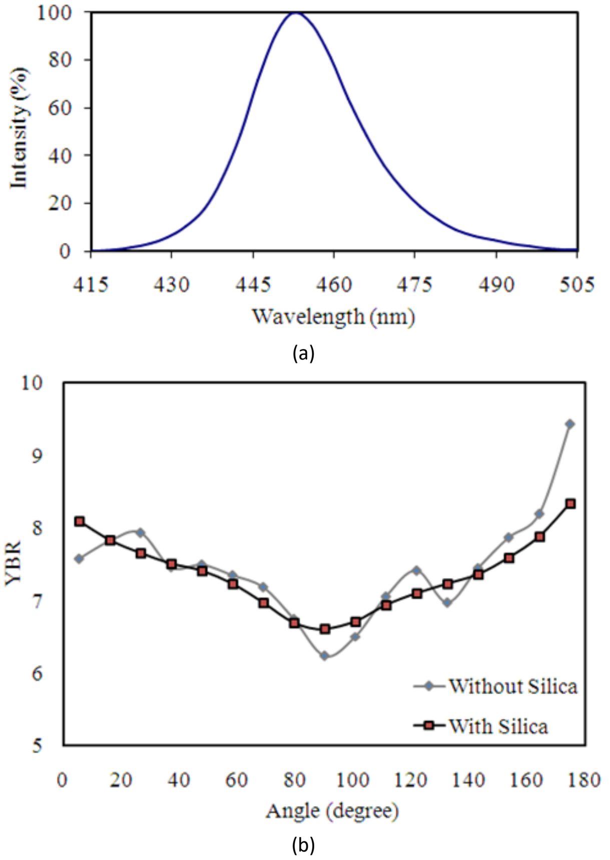

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Figure 3. Emission spectrum of each blue chip (a) and the spectra of the phosphor material (b).

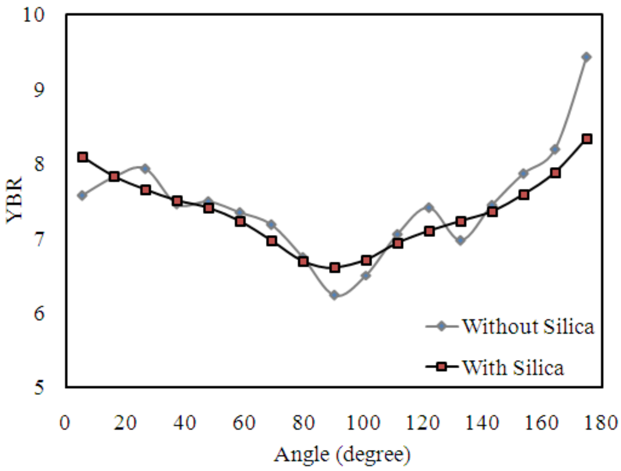


Figure 4. YBR curves (10% SiO_2 and without SiO_2).

SiO2 Particle Scattering

Silica (also called silicon dioxide, SiO_2) exists in many forms including melanophlogite, tridymite, and quartz (Fig. 5) [14, 15]. Quartz has excellent thermal and chemical stability and is easily available, and was thus used for this study [16]. Quarts was integrated into the phosphor layer as an essential portion of the MCW-LEDs originally composed of silicone and phosphors. In Fig.6, the refractive index and the density of the SiO_2 particles are respectively set at 1.54 and 2.65.

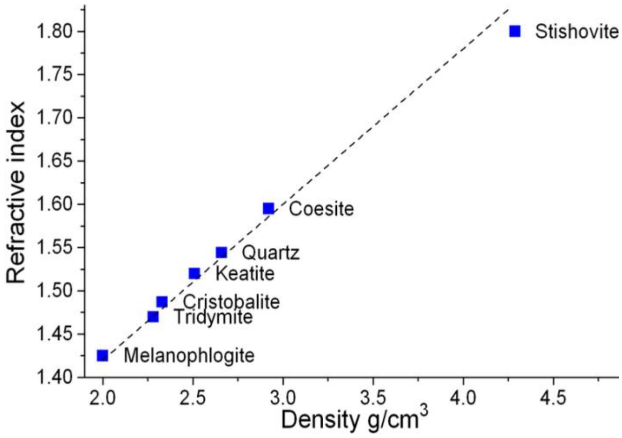
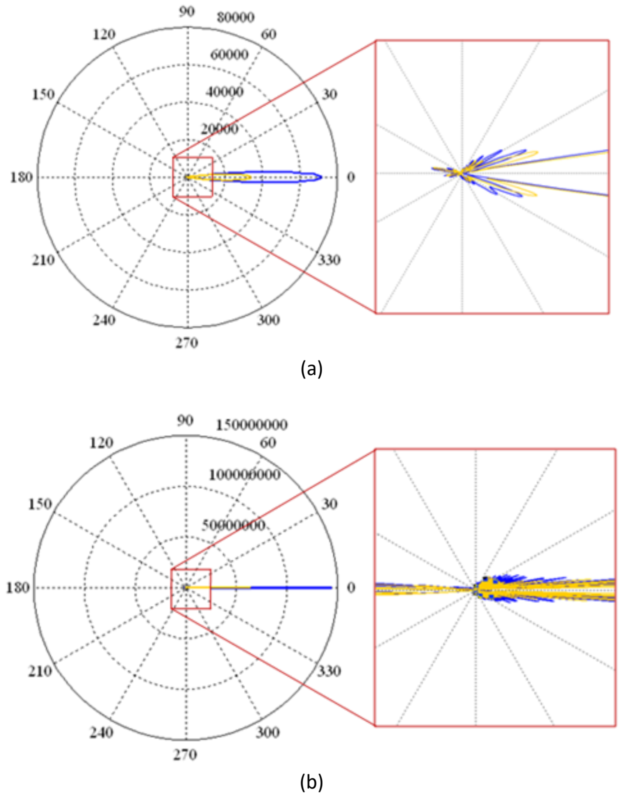


Figure 5. Relation between the refractive index and the density of SiO2 compositions.



(a)

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Figure 6. Angular Mie-scattering diagram of the SiO2 particle (a) and of the phosphor particle (b).

We use Mie theory in MATLAB software to compute the scattering of both the SiO_2 and the phosphor particles.

Mie theory is also applied to calculate the angular scattering functions over the entire scattering range, with θ from 0^0 to 360^0 [6]. Furthermore, the angular scattering amplitudes could be demonstrated by:

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

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

where $\pi_n(\cos\theta)$ and $\tau_n(\cos\theta)$ could be calculated with using the Legendre polynomials:

$$\pi_n(\cos\theta) = \frac{P_n^{(1)}(\cos\theta)}{\sin\theta} \quad (3)$$

$$\tau_n(\cos\theta) = \frac{dP_n^{(1)}(\cos\theta)}{d\theta} \quad (4)$$

Then $a_n(x,m)$, $b_n(x,m)$, and x are defined as:

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

$$b_n(x,m) = \frac{m\psi_n^{'}(mx)\psi_n(x) - \psi_n(mx)\psi_n^{'}(x)}{m\psi_n^{'}(mx)\xi_n(x) - \psi_n(mx)\xi_n^{'}(x)} \quad (6)$$

$$x = 2\pi a / \lambda \quad (7)$$

where a is the spherical particle radius, λ is the relative scattering wavelength, m is the refractive index of the scattering particles, and ψ_n , ξ_n are the Riccati - Bessel functions.

To compute the size parameters, two dominant wavelengths are traced. The first one is 453 nm, corresponding to the blue light which is the emission peaks of the LED chips. The other is 555 nm, representing the yellow light which is the emission peaks of the phosphor. Fig. 6 presents the difference between the scattering intensity distributions of the SiO_2 particle and that of the phosphor particle. The single phosphor particle absorbs and scatters incident light, while the single silica particle only scatters incident light. Therefore; the scattering process of the PSL is enhanced. From these results, the CCT angular distribution of the MCW-LEDs could reconfigure and perform better when SiO_2 particles are added to the phosphor layer.

Spatial Color Distribution Analysis

Lumen output and CCT uniformity of different particle concentrations were compared and analyzed. Lumen output was characterized by the luminous flux (lm) escaping from the package; while CCT deviation was calculated by the subtraction of maximum CCT by minimum CCT, and CCT angular uniformity was characterized by CCT deviation. In this research, the phosphor and silica concentration were changed to control the CCT of the MCW-LEDs at 7700 K. On the other hand, the weight percentage of the SiO_2 increases from 5% to 30% and the phosphor concentration must be reduced from 29.79% to 25.15% to keep the CCT at 7700 K. Finally, the total weight percentage of the phosphor layer is the sum of three component types: the silicone, the phosphor, and the SiO_2 in the phosphor compound.

Figure 7 shows the spatial color distribution with 10% weight of silica in the phosphor layer and without SiO_2. The angular color temperature in the central angles is much better than that of the inside angles without SiO_2. With silica, the center of the color temperature is close to the side color temperature. This version shows significant advantages for obtaining uniform white light by adding SiO_2. The CCT deviation is seen to fall from 2211 K to 1719 K due to moderate mixing between the blue and yellow rays emitted from the MCW-LEDs following the addition of SiO_2.

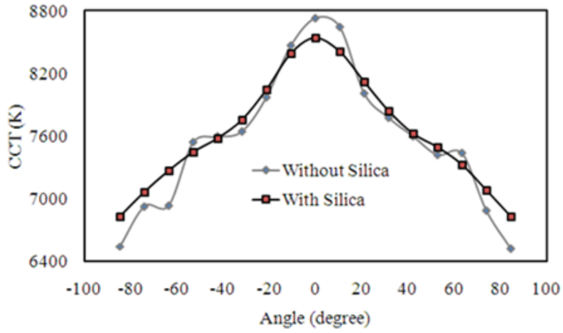


Figure 7. Angular CCT distributions with and without 10% weight SiO2.

Figure 8 presents the CCT deviation and luminous efficiency of different SiO_2 particle concentrations from 0% to 30%. From these results, the overall tendency of the low CCT deviations occurs at SiO_2 concentrations of about 10%. On the other hand, the lumen output may not be influenced by the SiO_2 concentration. In summary, the addition of SiO_2 to 7700 K MCW-LEDs can produce better CCT uniformity.

Ray tracing was executed with 5,000,000 rays. To supervise the illumination distribution, simulations were performed using the proposed PSL with a 10 % SiO_2 weight. Figure 9 shows the illuminance maps with the same contour scales. The illumination distribution is more uniform with 10 % weight of silica, with illuminance uniformity in the MCW-LEDs increasing from 0.328 to 0.353 (Fig. 10). The proposed PSL structure increases the divergence angle of the blue light rays. As this angle increases, the difference between the central and the large angle is reduced. In contrast, for the conventional

PSL structure, the blue rays are concentrated in a narrow direction and pass through without combining with yellow rays in outside direction. Thus, the proposed PSL structure produces a higher IU than conventional PSL.

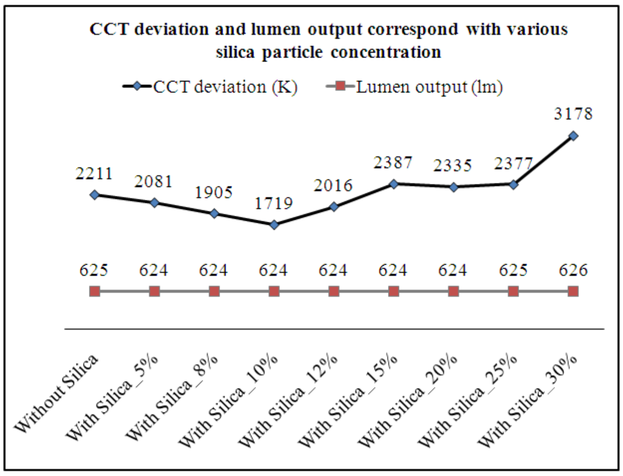


Figure 8. CCT deviation and lumen output at 7700 K for different SiO2 concentrations.

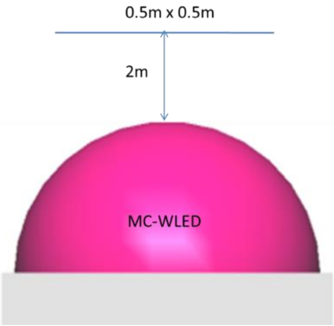
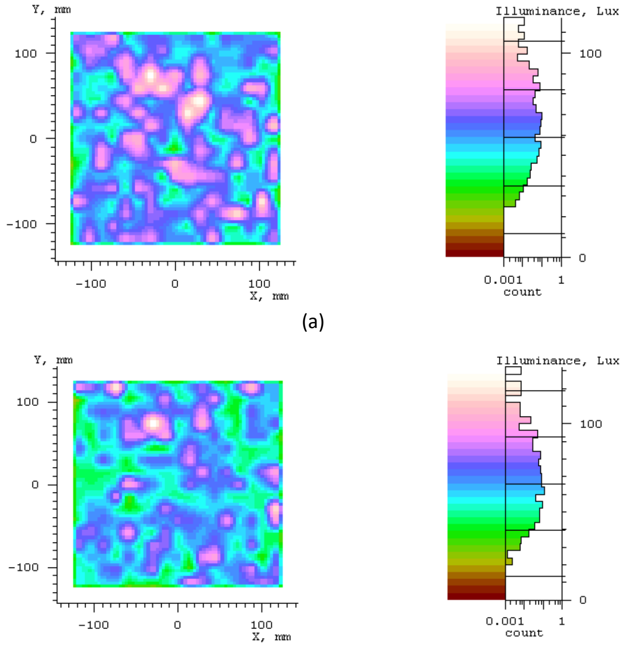


Figure 9. A 0.25 x 0.25 m^2 detector was placed at a distance of 2 meters in front of the MCW-LEDs.



(a)

(b)

Figure 10. Comparison of illuminance maps for the non – silica case (a) and the 10 % weight of silica case (b).

Conclusion

The CCT uniformity and lumen output of MCW-LEDs are measured following the addition of SiO_2 particles into the PSL. Results indicate that the proposed PSL with a SiO_2 weight of around 10% produces the best ACU with a lowest CCT deviation around 1719 K. The proposed PSL also increases the IU distribution over the target area, and illuminance uniformity was increased from 0.328 to 0.353. SiO_2 weight was varied to observe its impact on CCT deviation. Only one type of conformal MCW-LED package with 7700 K color temperature was studied. Based on the results, we can predict the compositional parameters needed to optimize the MCW-LEDs package. Moreover, based on the proposed method, other package types, such as in-cup phosphor and remote phosphor packages, could also be improved in the near future.

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