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Enhancement Spatial Color Uniformity of White Light LED Lamps by Adding Silicon Dioxides in Phosphor Layer

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Abstract

Recently, high-power light-emitting diodes (LEDs) have attracted great attention on the study and made remarkable progress. In this paper, method for enhancing uniform white light of a multi-chip white light LED by adding silicon dioxides in the phosphor layer is presented. Firstly, theory of study by using Mie theory and Monte Carlo ray-tracing is proposed. And then simulation and experimental results by using package LightTools software are performed. The experimental results and theory have the same direction: 1) the angular color temperature in narrow angles is much higher than that in wider angles for the non-SiO_2 case and 2) in significantly reducing CCT deviation of a multi-chip white light LED by adding silicon dioxides in the phosphor layer.

Keyword*: Color uniformity, multi-chip white light LEDs, phosphor, silicon dioxide*

1. Introduction

Correlated color temperature (CCT) uniformity is one of the most important performance factors for white light LEDs [1, 2]. So far, several studies have been proposed to improve the color uniformity of LEDs by optimizing the state of the phosphor or the optical structure of phosphor-converted white light LEDs (PC-LEDs). It was shown the spatial color uniformity of PC-LEDs can be controlled by the thickness and the concentration of the phosphor [3, 4]. Moreover, it was found the location of phosphor material in the silicone layer can affect the color performance. Sommer *et al*. [5] has demonstrated that refractive indexes of the silicone matrix, and the phosphor particle as well as the distinct phosphor particle sizes strongly effect on the color temperature of PC-LEDs. In this study, silicon dioxides (SiO_2) particles are applied in the phosphor layer of a multi-chip white light LED (MCW-LED) to improve the color uniformity. We demonstrate the participation of the SiO_2 particles can dominate the light scattering process in the phosphor layer, so that the LED light distribution can be independent of its wavelength. The uniform spatial color distribution of the LED can be accomplished.

2. Theory and Model

2.1. Simulation Model

Based on Monte Carlo ray-tracing method, we simulate the lumen output and CCT of a real MCW-LED. Its phosphor layer mechanism, with flat silicon structure, is constructed by using Light Tools 7.3.0 software. The main work procedures shown as follow: 1) building

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the precise mechanical parameters and the optical components of the MCW-LED; 2) enhancing the scattering of phosphor layer with SiO2 particles to improve the angular CCT deviation of the MCW-LED. 3) demonstrating the simulation of MCW-LED model has results close to the real MCW-LED sample; To conduct the optical simulations, we build a 3-D model as shown in Figure 1. Figure 1(b) shows the structure of phosphor layer. The reflector has a bottom length of 8 mm, a height of 2.07 mm and a length of 9.85 mm at its top surface. The phosphor layer covering the 9 LED chips has the fixed thickness 0.08 mm. Each LED chip with a square base of 1.14 mm and a height of 0.15 mm is bonded in the cavity of the reflector shown in Figure 1(a). The radiant flux of each blue chip is 1.16 W, which peak wavelength is 453 nm.

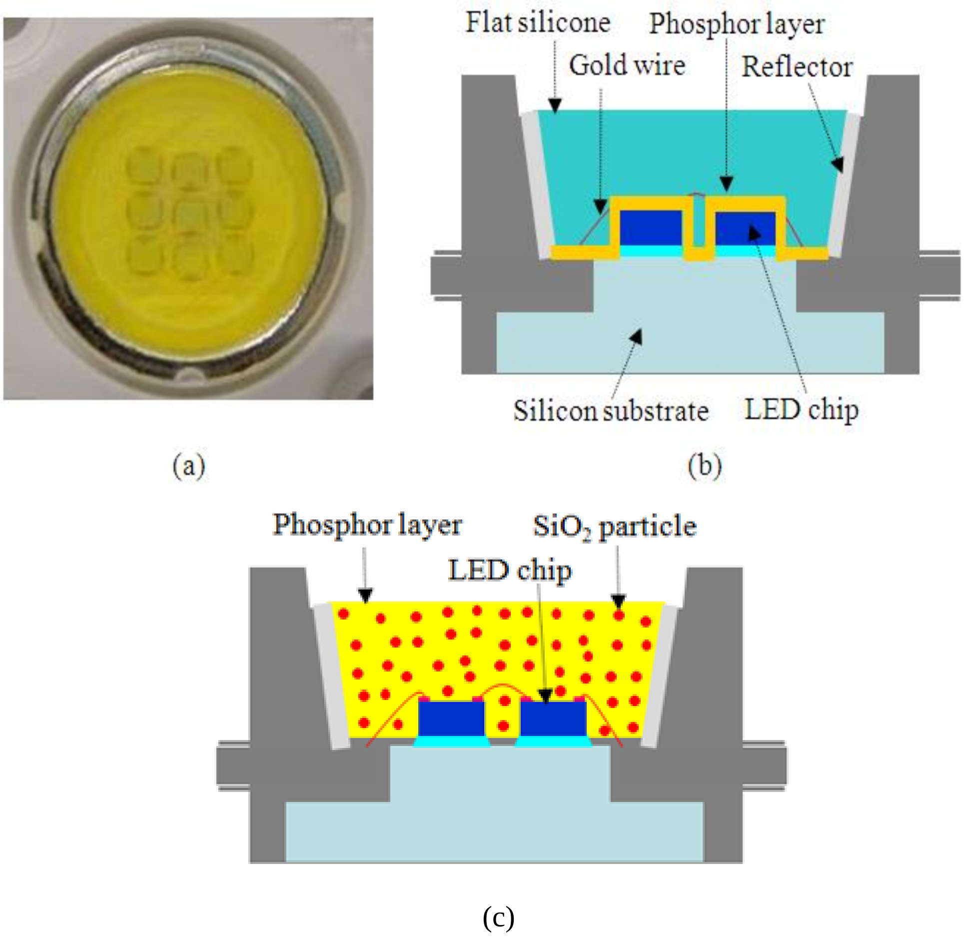

Figure 1. (a) MCW-LED Appearance, (b), (c) MCW-LED Structure

The chemical compound of silicon dioxide, also known as silica, is an oxide of silicon with the chemical formula SiO2 which has some constitutions such as melanophlogite, tridymite, quartz, and so on, see Figure 2 [6, 7]. Quartz is widely used in many industries because of its high thermal and chemical stability and abundance [8]. In this study, we added quartz (SiO2) in the phosphor layer, while still keep silicone matrix and phosphor structure as origin. According to Figure 2, we set the refractive index and the density of the quartz particles as 1.54 and 2.65 g/cm^3 in our experiments respectively. In the simulation, new phosphor layer includes the silicon dioxide particles and the phosphor particles as well as the silicone matrix. The average radius of the phosphor particles and the SiO2 particles are set to be 7.25 µm and 6 µm respectively. The silicon dioxide particles and the phosphor particles are mixed together with the silicone glue uniformly and coated on the surfaces of the LED chips. Phosphor particles are assumed to be spherical and have refractive index of 1.83 at all wavelengths of light. The refractive index of the silicone matrix is set as 1.52, the same as the actual material. In order to appraise the similarity between our MCW-LED model and the real MCW-LED sample, we compare them by using the normalized cross correlation (NCC) in intensity angular distribution [9, 10].

$$NCC = \frac{\sum_n [I(\theta_n)_e - \overline{I_e}][I(\theta_n)_s - \overline{I_s}]}{\sqrt{\sum_n [I(\theta_n)_e - \overline{I_e}]^2 \sum_n [I(\theta_n)_s - \overline{I_s}]^2}} \quad (1)$$

Here Is and Ie are the simulated and real experimental values of the relative light intensity, respectively. θn is the n-th angular displacement, $\overline{I_s}$ and $\overline{I_e}$ are the mean values of simulations and optical measuring experiments accomplished by a gomiophotometer across the angular range.

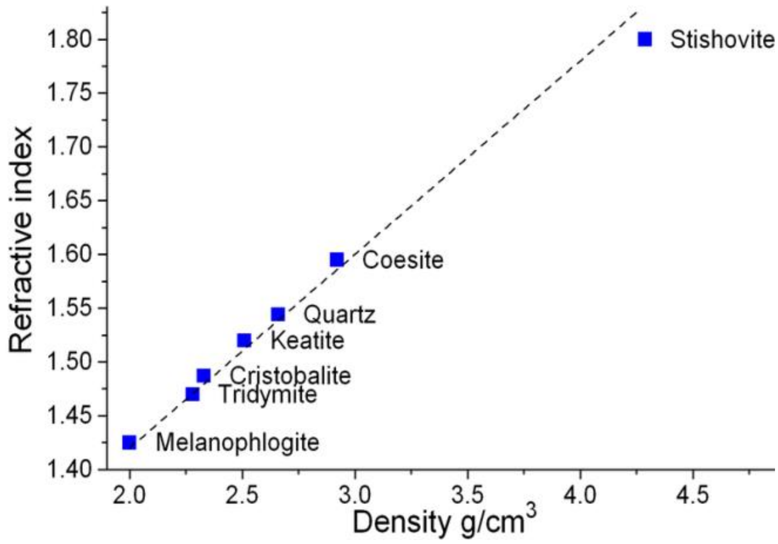

Figure 2. The Relation between the Refractive Index and the Density of Sio2 Forms

The NCC related experimental results are shown in Figure 3, showing the discrepancy between the computer simulation and the optical measurements in the angular intensity distribution from -90 to +90 degrees. The NCC value overcomes 99.5%, proving that the LED simulation model satisfy necessary accuracy to improve white light uniformity.

2.2. Study Theory

Through the MCW-LED model, we obtain the blue light and the yellow light intensity distribution in polar coordinates shown in Figure 3, respectively. After calculating and combining these intensity data, the color temperature of the MCW-LED with respect to angles can be realized.

To clarify more the reason for the uniform CCT as our above results, a simplified analytical model was applied which presented the scattering of a phosphor particle and a quartz particle in accordance with Mie theory. In this work, we applied Mie theory to compute the angular scattering functions over the entire range of scattering angles, θ from 0 to 2π [3, 12]. The angular scattering amplitudes, S_1 and S_2, can be analyzed by the relationship:

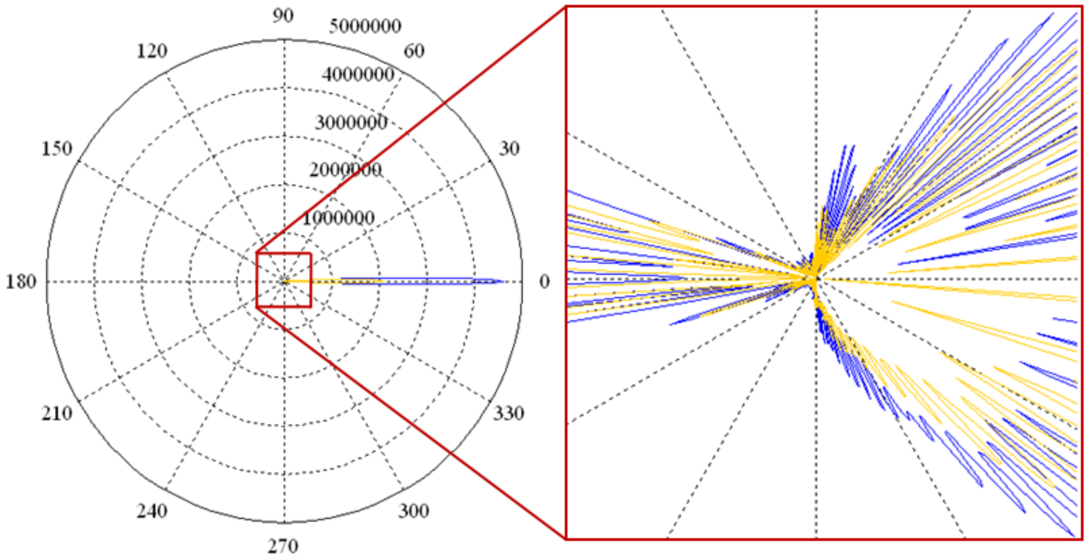

Figure 3. Blue and Yellow Light Intensity Distribution of MCW-LED

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

$$S_2 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[a_n(x,m)\tau_n(\cos\theta) + b_n(x,m)\pi_n(\cos\theta) \right] \tag{3}$$

In (2) and (3), the angular dependent functions $\pi_n(\cos\theta)$ and $\tau_n(\cos\theta)$ are expressed in terms of the Legendre polynomials by:

$$\pi_n(\cos\theta) = \frac{P_n^{(1)}(\cos\theta)}{\sin\theta} \tag{4}$$

$$\tau_n(\cos\theta) = \frac{dP_n^{(1)}(\cos\theta)}{d\theta} \tag{5}$$

The parameters a_n and b_n are defined as:

$$a_n(x,m) = \frac{\psi_n'(mx)\psi_n(x) - m\psi_n(mx)\psi_n'(x)}{\psi_n'(mx)\xi_n(x) - m\psi_n(mx)\xi_n'(x)} \tag{6}$$

$$b_n(x,m) = \frac{m\psi_n'(mx)\psi_n(x) - \psi_n(mx)\psi_n'(x)}{m\psi_n'(mx)\xi_n(x) - \psi_n(mx)\xi_n'(x)} \tag{7}$$

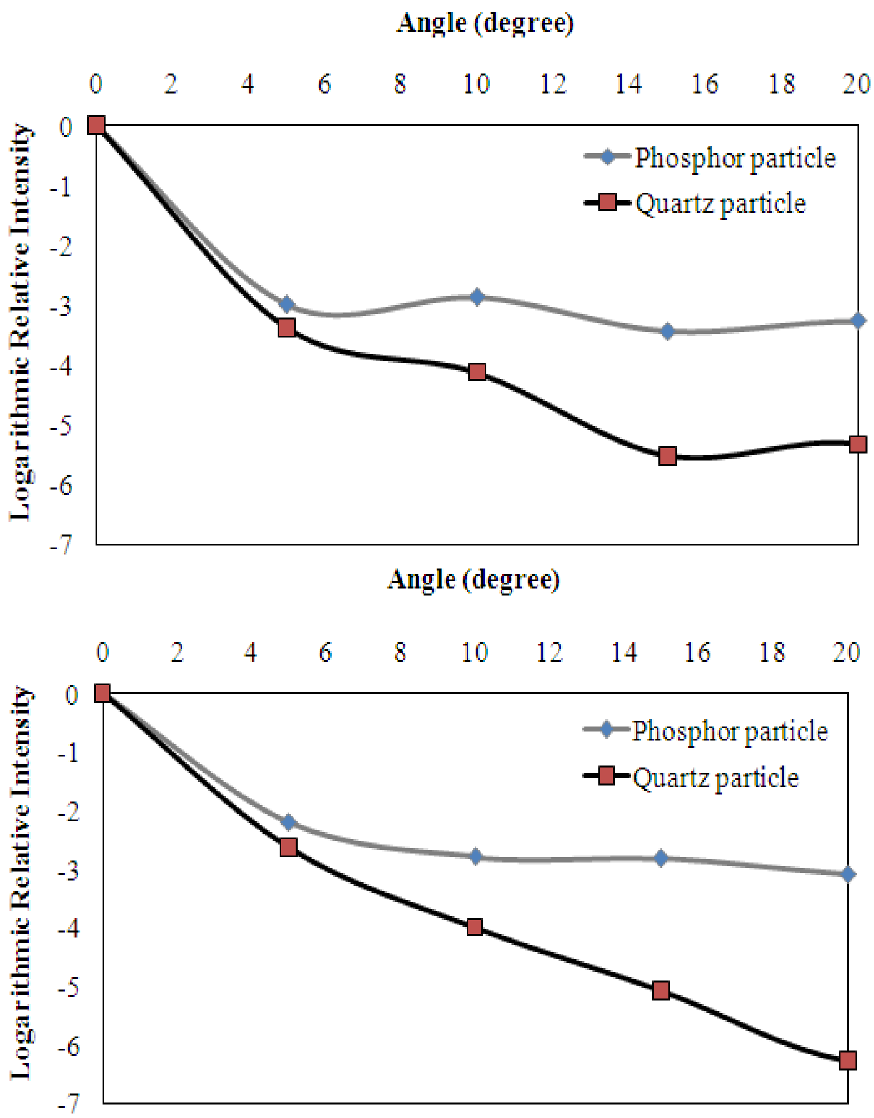

Figure 4. The Mie-Scattering Patterns of the Single Sio_2 Particle and the Single Phosphor Particle for (Top) 453 Nm and (Bottom) 555 Nm

The size parameter x is given by the expression as below:

$$x = 2\pi a / \lambda \tag{8}$$

Where a is the spherical particle radius, λ is the relative scattering wavelength, m is the refractive index of the scattering particles, $\psi_n(x)$ and $\xi_n(x)$ are the Riccati - Bessel functions. The size parameter is calculated for two distinct wavelengths, 555 nm and 453 nm, which are the emission peaks of the phosphor and the LED chips, respectively. Our computed results in Figure 4, showing that the scattering light intensity distributions by the single SiO_2 particle and the single phosphor particle are different. According to the results, the CCT angular distribution of the MCW-LED may also reconfigure and get better when we add SiO_2 particles in the phosphor layer.

3. Results and Discussion

In the experiments, we demonstrate the effect on angular CCT uniformity by adding quartz to the phosphor layer of the MCW-LED. To maintain the MCW-LED work at CCT mean 8500 K, we must adjust the concentration of phosphor particles and quartz particles by changing weight portions of them. If the weight percentage of the quartz is increased, for example, from 5% to 40%, the phosphor needs to be reduced from 29% to 22.78% for maintaining the CCT 8500 K.

$$\sum W_{pl} = W_{phosphor} + W_{silicone} + W_{quartz} = 100\% \quad (9)$$

The $W_{silicone}$, $W_{phosphor}$ and W_{quartz} are the silicone, the phosphor and the quartz weight percentage of the phosphor layer in the MCW-LED respectively.

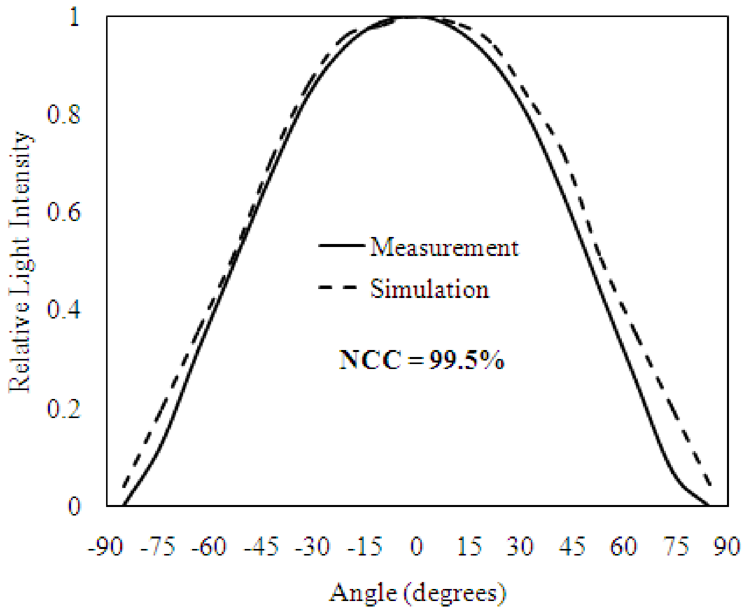

Figure 5. The Simulated Light Distribution Curve versus the Optical Measured One of the MCW-LED

Figure 6, shows the experimental results which compare the angular CCT distributions for 10% weight of quartz and without it. It can be observed that the angular color temperature in narrow angles is much higher than that in wider angles for the non-SiO_2 case. After adding SiO_2, the CCT deviation drops from 3086 K to 1956 K, which indicates that we can accomplish the 8500K MCW-LED with better CCT uniformity. In Figure 7, 8 the experimental results of the 7000K, 5600 K MCW-LED are shown separately. From the experimental results, the angular color temperature in narrow angles is much higher than that in wider angles for the non-SiO_2 case and CCT deviation decrease rapidly.

In the connection with studying the impact of SiO_2 concentration on CCTU of the MCW-LED, we increase the weight percentage of SiO_2 from 0% to 40% continuously. Referring to the accomplished experimental results in Figure 9, it can be found that the lowest CCT deviation occurs in the 10% SiO_2, and the lumen output seems not impacted by the SiO_2 concentration.

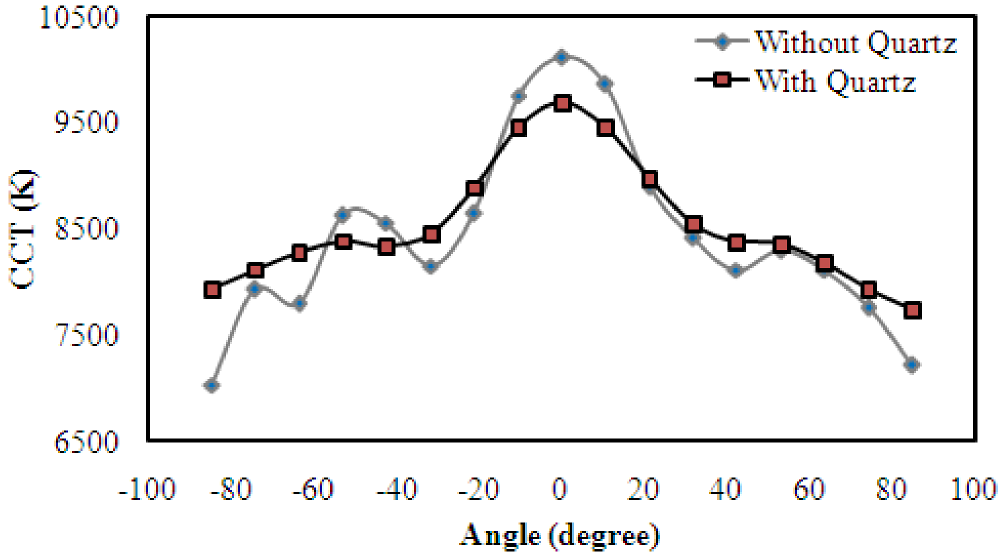

Figure 6. The Angular CCT Distributions For 10% Weight of Quartz and Without It (8500K)

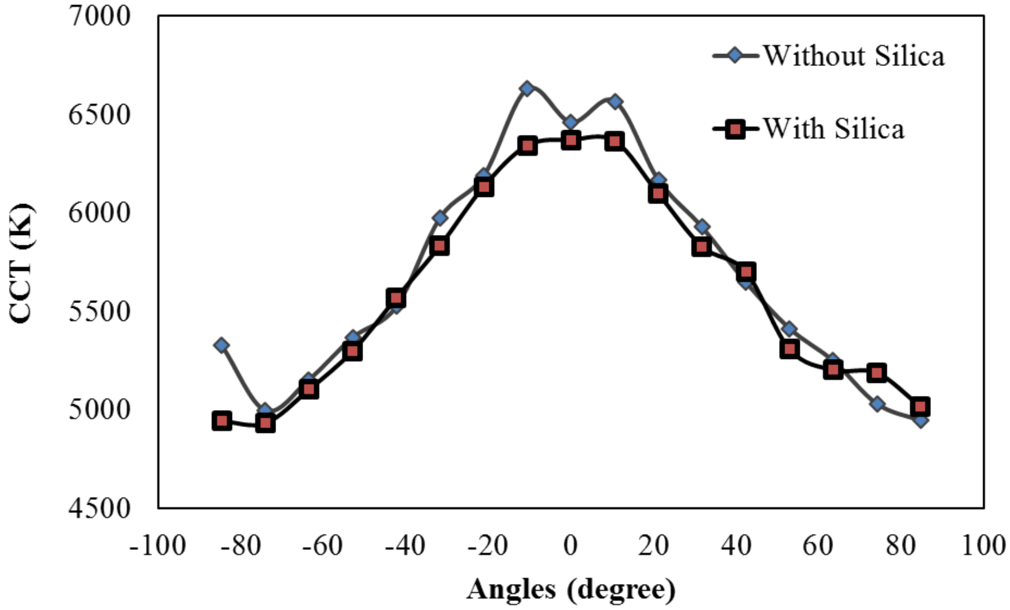

Figure 7. The Angular CCT Distributions For 10% Weight of Quartz and without it (7000K)

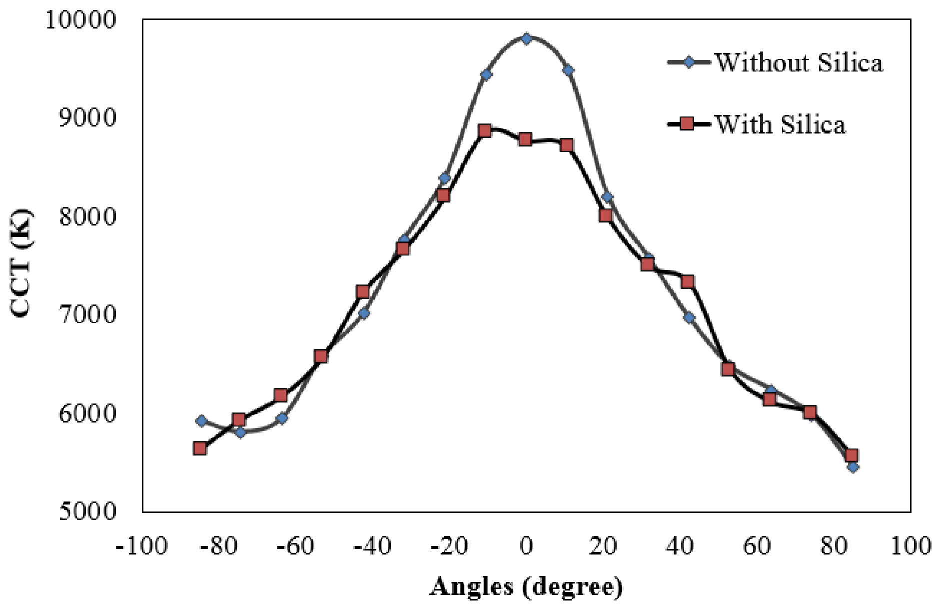

Figure 8. The Angular CCT Distributions For 10% Weight of Quartz and Without It (5600K)

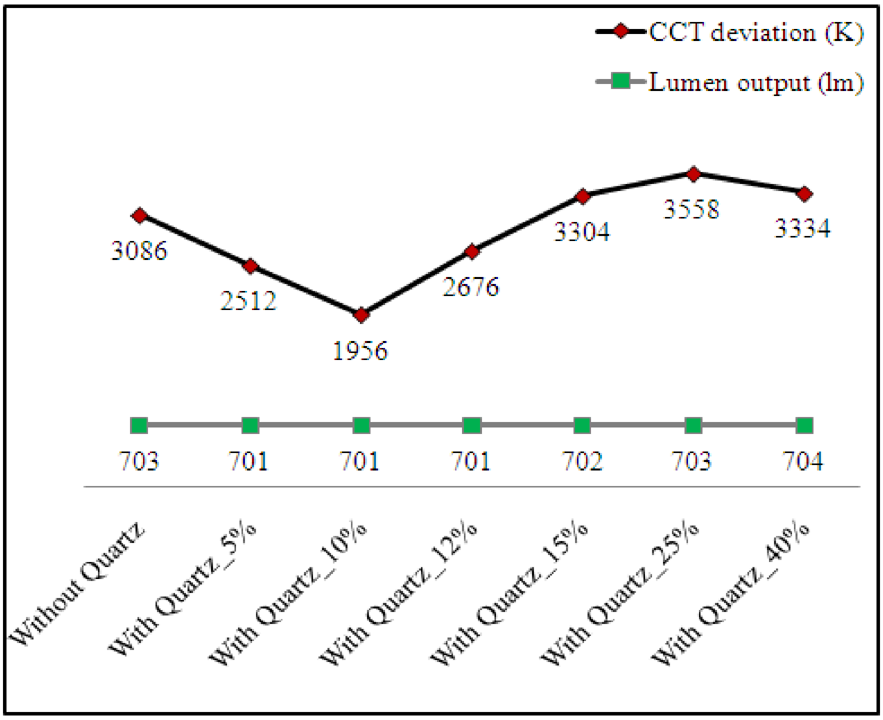

Figure 9. CCT Deviations and Lumen Output At 8500 K for Different Quartz Concentration Cases

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5. Conclusion

From theory, simulation and experimental results, some conclusion are proposed:

1) The angular color temperature in narrow angles is much higher than that in wider angles for the non-SiO_2 case and CCT deviation significantly reduced with the participation of SiO_2. The CCT deviation from -90 to 90 degrees was improved to 1956 K from 3086 K after mixing SiO2 particles in the phosphor layer

2) The lowest CCT deviation occurs in the 10% SiO_2, and the lumen output seems not impacted by the SiO_2 concentration.

3) The paper provides important technical parameters for the development of PC-LEDs products.

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