Silica particles: an innovative recommendation for enhancing the color uniformity and illuminance efficacy of multi-chip white LED lamps

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In this paper, the effect of silica particle (SiO_2) concentration on color and illuminance uniformity of a multi-chip white LEDs (MCW-LEDs) with the correlated color temperature (CCT) near 8500 K is presented and analyzed. It is suggested that the novel phosphor silicone layer (PSL), which is added by silica particles, can improve the uniformity of color correlated temperature (CCT) and illumination. By using LightTools simulation program based on Monte Carlo method, the novel PSL enables the reduction of the CCT deviation (ΔCCT) from 2200 K to 1700 K, while the illuminance uniformity increases from 0.32 to 0.35. The simulation results could be totally proved by Mie theory. This research proposes a prospective approach for high quality manufacturing MCW-LED in the near future.

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Keywords: Multi-chip white light LED lamps, Silica, Quartz, Color uniformity, Illuminance

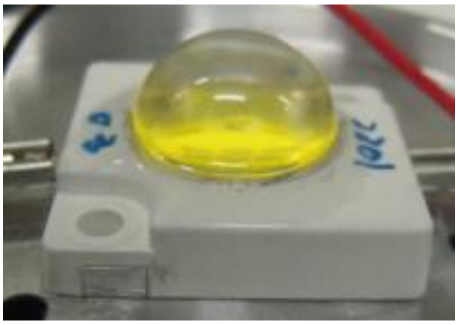
1. Introduction

Due to the low cost, small size, environmentally friendly process, long-life, compactness, and high luminous efficiency, white light-emitting diodes (LEDs) have been considered as the future-generation light source (Pimputkar et al., 2009, Schubert, et al., 2005, Chen, et al., 2012). Angular color uniformity (ACU) and illuminance uniformity (IU), in general, are the key optical properties in design to improve the light extraction. Because of some advantages of MC-WLEDs regarding to the efficiency, compactness, stability as well as lifetime, there is some rapid development of phosphor silicone layer (PSL) for obtaining higher quality of those factors. For improving ACU, many methods have been proposed. In particular, the IU could be improved by changing the PSL structure of white light LEDs package while optimizing the other components of MC-WLEDs package, such as, Fresnel lens, array of LEDs, patterned reflectors (Kuo-Ju Chen et al., 2013, Huai Zheng et al., 2012, Kim et al., 2009, Kim et al., 2010, Qin et al., 2010).

The conventional PSL of the popular white light LED structure contains uniformly distributed phosphor YAG:Ce particles and the silicone glue.

The PSL absorbs the exciting blue light from the chips to generate the yellow light and this combination results in the white light. Because of difference in the luminous intensity distribution of the phosphor-scattered blue light and the phosphor-emitted yellow light, the spatial color distribution of light LEDs becomes non-uniform. A non-optimized LEDs packaging may suffer from the unexpected phenomena such as yellow ring which can be found in our MCW-LED products as shown in Fig.1. During the multi-scattering process, the blue light is weakened because of the absorption of phosphorus, but the converted yellow light is enhanced after each scattering event. Therefore, the final ACU of white LED significantly depends on the scattering effects of PSL. It means that white light uniformity is more optimized as the scattering of PSL is enhanced (Liu et al., 2011).

The size, thickness, concentration, and the refractive index of the phosphor are four important factors for adjusting the scattering of PSL. Based on these criteria, white light quality has been also improved time by time. It has been studied by many research groups (Christian Sommer et al., 2011, Liu et al., 2008, N. T. Tran et al., 2009, J.L. Huang, et al., 2016, X.B. Luo, et al., 2016, and M. Cai, et al., 2016).



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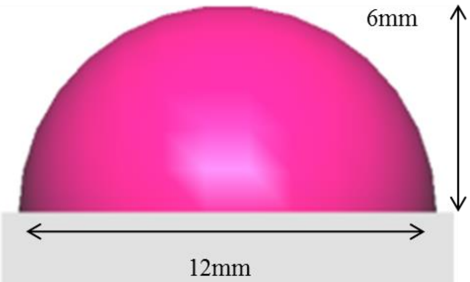

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Fig. 1. a) Real physical model of MCW-LEDs; b) Simulation model of MCW-LEDs; c) The phenomenon of yellow ring in the experimental MCW-LEDs

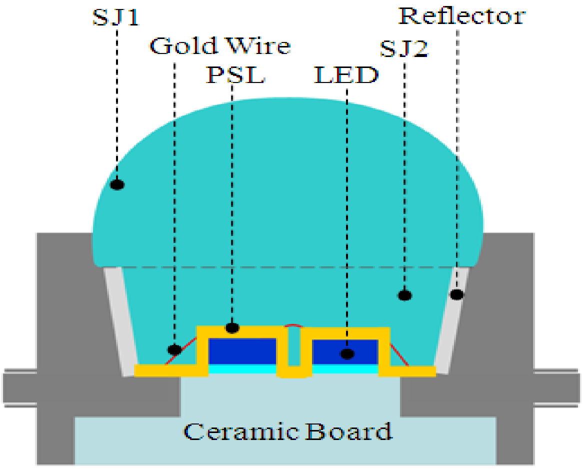
In this paper, the application of silica particles SiO_2 in the PSL of MCW-LEDs for improving the color uniformity and illumination is proposed. This research work could be divided into 3 sections: 1) Optical simulation model of MCW-LEDs based on Monte Carlo method is presented by the commercial LightTools software; 2) Scattering effect caused by silica particles SiO_2 is analyzed based on Mie theory and demonstrated by MATLAB software; 3) Spatial color distribution analysis and illumination uniformity verification are also provided convincingly. The results clearly testify that the participation of the silica particles dominate the light scattering process in PSL so that the spatial color and the illumination distribution could be uniformed. This research provided a prospective solution for high quantity MCW-LED manufacturing in the near future.

2. Simulation Model and Scattering Analysis

2.1. Optical Simulation Model

We use Monte Carlo method to simulate the PSL structure of an MC-WLEDs with the support of LightTools software. For ray tracing simulation, a thin PSL with the fixed thickness of 0.08 mm is used. The silicone lens, which are denoted as SJ_1 and SJ_2, cover 9 LED chips and are adhesive to the board. The refractive indices of SJ_1 and SJ_2 are 1.41 and 1.53, respectively. The radius of SJ_1 is 6mm while the height of SJ_2 is 2mm. Each LED chip, which has a square base of 1.14 mm^2 and a height of 0.15 mm, is bounded in on the center of the board.

The definition of the optical properties of the correct MCW-LEDs model and its PSL is critical [11-13]. It is expected that when the concentration of the silica is alternated, there would be a difference in optical performance for ACU and IU due to the scattering enhancement in the novel PSL.



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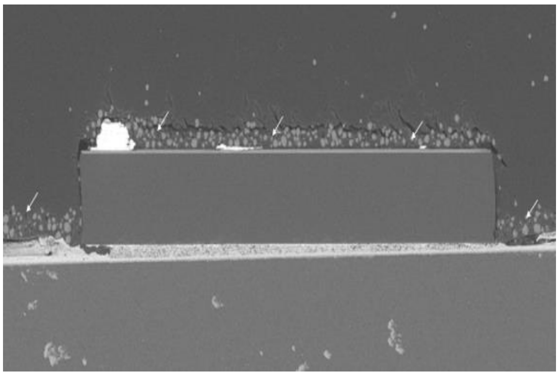

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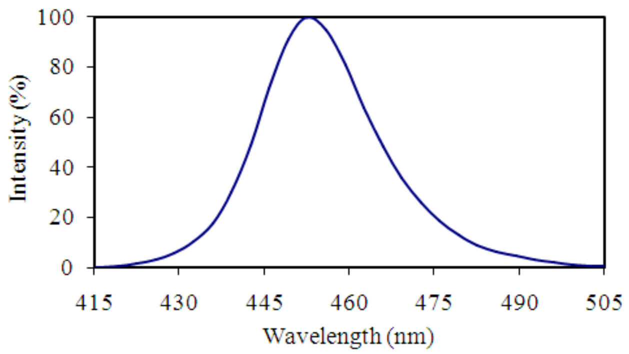
Fig. 2. (a) Schematic illustration of the optical structure of the actual MCW-LED and (b) SEM images of cross section of PLS structure

The novel PSL structure, which is used in our study, is resulted from the addition of the silica particles to the conventional PSL (Fig. 2). The refractive index of silica particles, phosphor particles, and silicone matrix are 1.54, 1.83, and 1.52, respectively, exactly the same as in actual materials. The silica and phosphor particles have the radii of 1 µm and 7.25 µm, respectively. The blue chip of MC-WLEDs have flux 1.16 W at wavelength 453 nm, see Fig.3.

The blue and yellow light intensity distribution are obtained in the conventional PSL by using simulation software. The yellow, blue ratio curves of the MCW-LEDs varying with respect to different angles can be achieved by analyzing these data. The results in Fig. 4 show that the conventional PSL structure has severe deviation ratio. On the other hand, the novel PSL structure can maintain the higher ratio consistently from 0 to 180 degrees. From that point, the conventional PSL structure has worse geometric color mixing effect than the novel PSL structure does.



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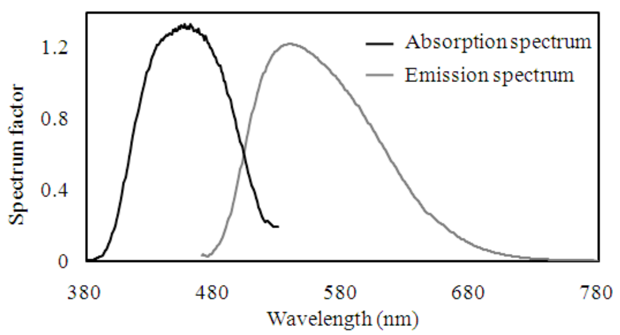


(b)

Fig. 3. The emission spectrum of each blue chip (a) and the spectra of the phosphor material (b)

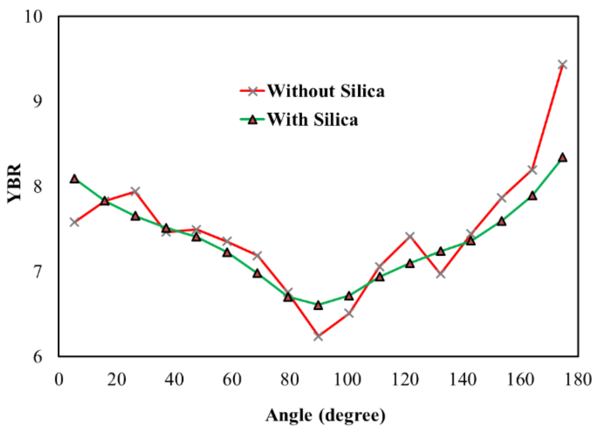


Fig. 4. The YBR curves (10% SiO_2 and without SiO_2)

2.2. Scattering of the SiO_2 particles

Silica is an oxide of silicon with the chemical formula SiO_2 or known as the chemical compound silicon dioxide. In reality, it exists in several forms. For instance, melanophlogite, tridymite, quartz, and so on (Fig. 5) [17, 18]. In this research, quartz, which has excellent thermal and chemical stability and abundance was used [19]. It is added into the phosphor layer as an essential portion of the MCW-LED, which is composed of silicone and phosphors originally. In Fig.6, the refractive index and the density of the SiO_2 particles are set as 1.54 and 2.65 in the experiments, respectively.

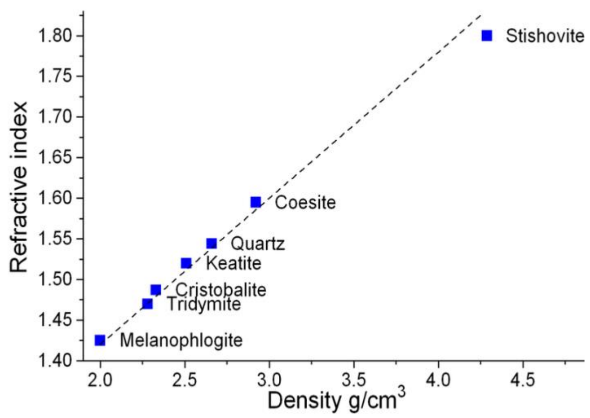


Fig. 5. The relation between the refractive index and the density of SiO_2 compositions

We use Mie theory with the support of MATLAB software to compute the scattering of both SiO_2 and phosphor particles. In addition, 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 by using the Legendre polynomials:

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

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

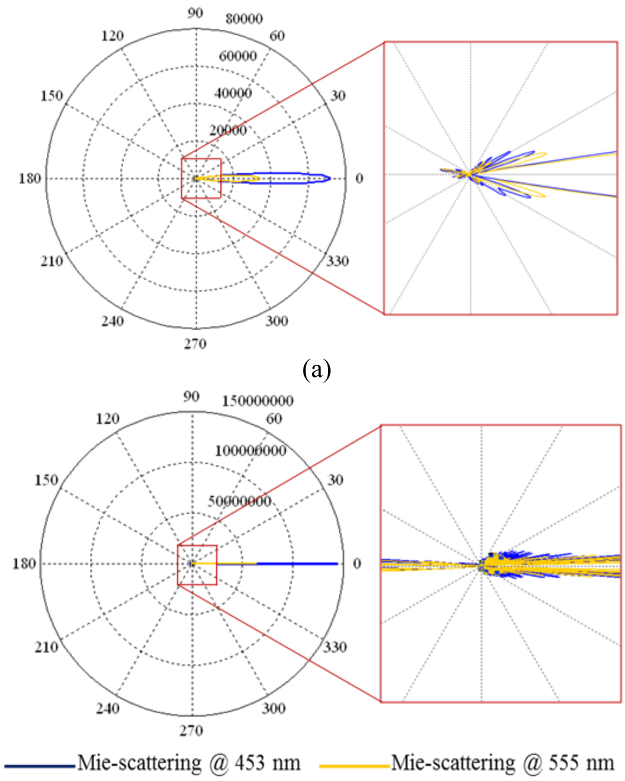
Here, $a_n(x,m)$, $b_n(x,m)$, and x are defined as:

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

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

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

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.



(a)

(b)

Fig. 6. Angular Mie-scattering diagram of the SiO_2 particle (a) and of the phosphor particle (b)

Two dominant wavelengths are traced to compute the size parameter. 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 particles and that of the phosphor particles. The single phosphor particle absorbs and scatters incident light, while the single silica particle only scatters incident light. As a result, the scattering process of the PSL is enhanced. From these results, the CCT angular distribution of the MCW-LEDs could be reconfigured, and hence, MCW-LEDs can perform better when SiO_2 particles are added in the phosphor layer.

3. Results and discussion

3.1. Spatial Color distribution analysis

Lumen output and color correlated temperature (CCT) uniformity at different particle concentration values are compared and analyzed. Lumen output is characterized by the luminous flux (lm) escaping from the package; while CCT deviation, which is characterized for CCT angular uniformity, is calculated by the subtraction of maximum CCT by minimum CCT. In this research, the phosphor and silica concentration are changed to control the CCT of the MCW-LEDs at 8500 K. In another way, the weight percentage of the SiO_2 increases from 5% to 30%, the phosphor concentration must be reduced from 29 % to 25 % to maintain the CCT value at 8500 K. Here, the total weight percentage of the phosphor layer is the sum of three types of components, including silicone, phosphor, and SiO_2 in the phosphor compounding.

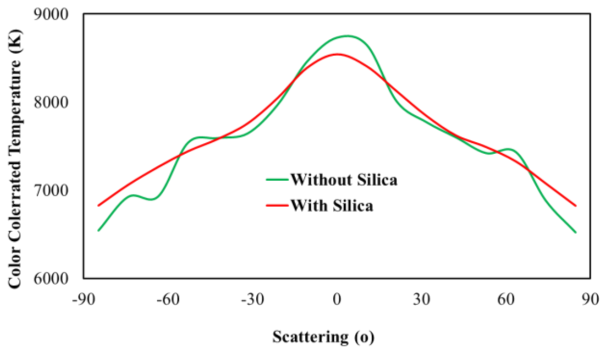


Fig. 7. The angular CCT distributions in case of 10% weight SiO_2 and without it

Fig. 7 shows the spatial color distributions with 10 % weight of silica in the phosphor layer and without SiO_2, respectively. The angular color temperature at central regime of the curve is much better than the outside regime for no-SiO_2 case. With silica, the central color temperature is closed to the side color temperature. In this version, it shows a significant benefit of obtaining uniform white light in the case that SiO_2 is added. Comparing between the

CCT deviation at 5 % weight of SiO_2 and without SiO_2, it can be observed that the CCT deviation drops from 2200 K to 1700 K due to moderate mixing between the blue and yellow rays emitted from the MCW-LED after SiO_2 is involved.

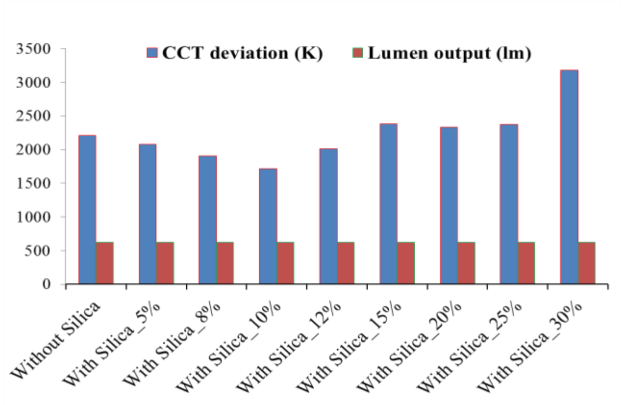


Fig. 8. CCT deviation and lumen output at 8500 K for different SiO_2 concentration

Fig. 8 presents the CCT deviation and luminous efficiency at various SiO_2 particle concentration, which ranges from 0% to 30% continuously. From these results, the low CCT deviations occurs around the 10% SiO_2. On the other side, the lumen output is not influenced by the SiO_2 concentration. In summary, the 8500 K MCW-LEDs with better CCT uniformity could be accomplished [23].

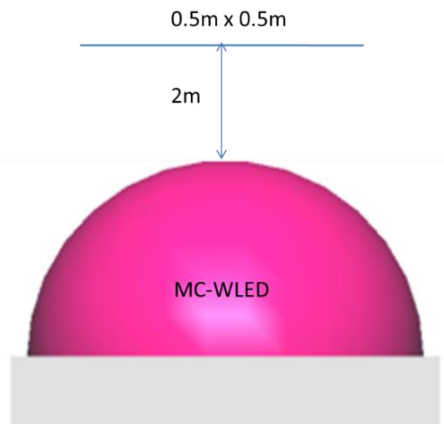


Fig. 9. A 0.25 x 0.25 m^2 detector was placed at a distance of 2 meters in front of the MCW-LEDs

3.2. Illumination uniformity verification

To testify the effect of SiO_2 on optical characteristic for the novel PSL structure, we measure the values of illuminance and calculate its deviation. A 0.25 x 0.25 m^2 detector is placed about 2 meters far from the MCW-LEDs by using LightTools and Trace Pro software (Fig. 9).

Ray tracing is executed with 5,000,000 rays by using LightTools and Trace Pro software. The simulations are performed with the novel PSL, which has 10 % weight of SiO_2, to supervise the illumination distribution. Fig. 10 shows the illuminance maps with the same contour scales. It can be observed that the illumination distribution is more uniform with 10 % weight of silica. After adding the SiO_2, the illuminance uniformity of MCW-LED has increased from 0.32 to 0.35, see Fig. 12. For the novel PSL structure, the blue light rays emit in larger divergent angle. As the distribution angle of blue ray increases, the difference between the central-region and the large-region angles would be reduced. In contrast, for the conventional PSL structure, the blue rays concentrate in a narrow direction and pass through without combining with yellow rays in outside this direction. This is the fundamental reason why the novel PSL structure has higher IU.

4. Conclusion

In this paper, the enhancement of CCT uniformity and lumen output of an MCW-LEDs by adding the SiO_2 particles into PSL are presented. It is proposed that the novel PSL with the weight of SiO_2 around 10% has the best ACU with lowest CCT deviation around 1700 K. Also, the IU distribution can be maximized over the target area compared to the conventional PLS structure. The illuminance uniformity could be increased from 0.32 to 0.35 with the novel PSL. More importantly, SiO_2 weight is varied to observe how CCT deviation changes with the novel PSL. In this work, we only studies one type of conformal package of an MCW-LEDs with 8500 K color temperature. Through the analysis method as well as simulation and experiment results, we can predict the compositional parameters which were necessary for optimizing the MCW-LED package. Moreover, based on the proposed method, other package types, such as in-cup phosphor, remote phosphor packages could also be improved in near future.

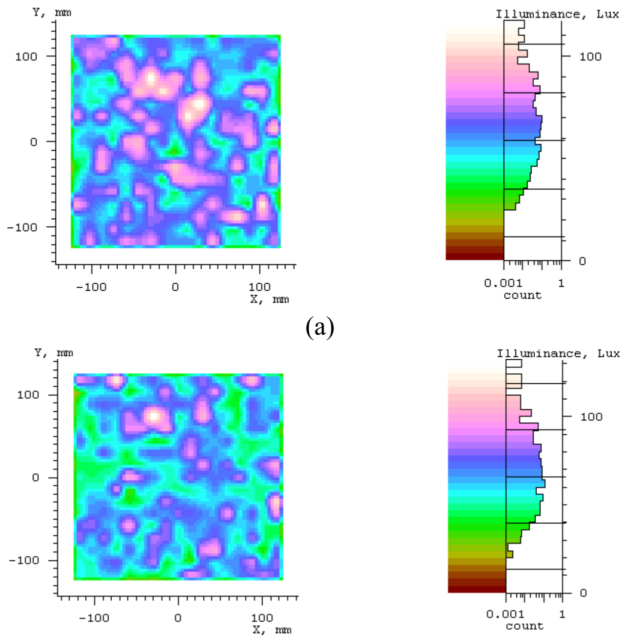


Fig. 10. Illuminance maps for the non-silica case (a) and the 10 % weight of silica case (b)

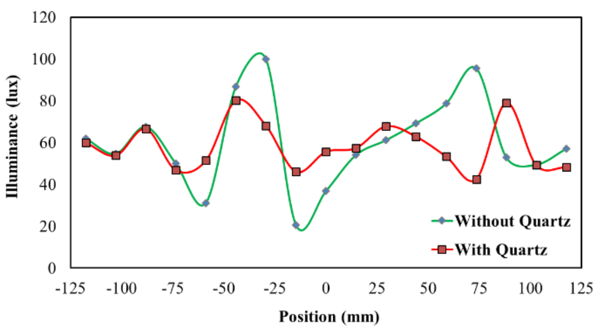


Fig. 11. Illuminance values for the 10 % weight of silica and without it

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