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Abstract

Phosphor-converted white light-emitting diodes (pc-WLEDs) are energy efficient and environmentally friendly light sources with a long lifetime, applicable in both display backlights and general lighting. In this research, we investigated the influence of the red-emitting $K_2SiF_6:Mn^{4+}$ conversion phosphor on the color quality of the 7000K conformal packaging multi-chip white LEDs (MCW-LEDs). The effect of the red-emitting $Ba_2Si_5N_8Eu^{2+}$ convention phosphor is demonstrated based on Mie Theory by Mat Lab and Light Tools software. The research results indicated that the color quality of MCW-LEDs was crucially affected by the red-emitting $K_2SiF_6:Mn^{4+}$ conversion phosphor's size. This research demonstrated a significant recommendation for selecting and developing the phosphor materials for MCW-LEDs manufacturing.

Keywords: *Red-Emitting Conversion Phosphor; MCW-LEDs; Color Quality.*

1. Introduction

Light-emitting diodes (LEDs) have found their way into many applications in daily life, from warm-white LEDs for energy-efficient lighting to display backlights for smartphones, tablets and televisions. The history of LEDs has been noticed more than a century. Already in 1907, H. J. Round published on light emission from a silicon carbide junction diode, the first light emitting diode (LED) ever. Independently, Losev observed emission from ZnO and SiC diodes, as published in 1927. At that time, the potential of the technology was not realized and the inventions remained largely unnoticed. It was not until 1962 that the first practical visible spectrum LEDs was developed, by Nick Holonyak at General Electric. In the decades that followed, LEDs were used extensively in numerical displays and signaling applications. However, only around 1995 high brightness and blue LEDs were developed, which made it possible to use LEDs for general lighting. Nowadays, LEDs use a mature technology which can compete with the traditional incandescent and (compact) fluorescent lamps. White light-emitting diodes (w-LED) are attracting tremendous attention in the recent years as a potential replacement for the conventional light sources because of their low electric consumption, high brightness, long lifetime, small size, robustness, fast switching, and environment friendly characters. Moreover, usinf LEDs can considered as a reduction of the worldwide electricity consumption. The current attention to energy saving and reduction of CO_2 emission in the atmosphere should therefore give an additional boost to the development of LEDs for lighting. Remaining disadvantages of LEDs are the need for extensive cooling of high power devices (ultimately limiting the maximum power per LED chip), the need for current driving and the lack of high color quality white LEDs [1-7]. There has been considerable research in the lighting community in an effort to fabricate white light sources using InGaN based LEDs. One popular approach to produce white light is the combination of blue-emitting InGaN LED with a yellow-emitting Y3Al5O12:Ce3+ (YAG:Ce3+) phosphor, but this type of white light suffers from poor color rendering index (CRI) due to the lack of a red light component. In the last few decades, there so many research focus on improving the optical performance of the pcLED in packaging direction. Thickness and concentration of phosphor are considered as the main factors in the white LEDs packaging because the luminous flux and color of LEDs are adjusted mainly through changing the phosphor thickness and concentration after the phosphor converters are chosen. Tran el al. [8,9] experimentally studied the effects of phosphor thickness and concentration on LEDs luminous flux and correlated color temperature. From the results, higher luminous efficacy are taken with the lower phosphor concentration and higher phosphor thickness (lower trapping efficiency and fewer backs scattering of light). Sommer et al. firstly studied the effects of phosphor thickness, concentration, and size on the spatial color distribution of white LEDs [10]. The spatial color uniformity of white LEDs could be improved by changing the phosphor concentration or thickness. An increase of the phosphor thickness or concentration can alter the color from bluish to yellowish, and the growth in the central zone is faster than that in the border area. In [11-14], the effect of phosphor location on the spatial color distribution was investigated. The results showed that to obtain high color uniformity, packaging elements should make the blue light and yellow light have a similar radiation pattern. In the last year, some researchers were concentrated on enhancing the optical performance of multi-chip white LEDs (MCW-LEDs) by adding green or red phosphor into the phosphor compounding [15-17]. It can be found that the optical properties of MCW-LEDs can be enhancing clearly. From this point of view, improving the color quality of MCW-LEDs by adding diffusers into the phosphor compounding is still needed to investigate. In this research, we try to fill the remaining gap.

As rare-earth-free alternatives, the manganese-based phosphors K_2SiF_6:Mn^{4+} has d-d transitions, which are partially spin-allowed for Mn4+. Upon incorporation in the host compound, Mn4+ is the preferred valence state for LED applications, due to better excitation properties and narrower emission bands. In K_2SiF_6:Mn^{4+}, the Intra configurational 3d3 transitions of the Mn4+ ion are responsible for the luminescence, yielding narrow line emission. Furthermore, K_2SiF_6:Mn^{4+} has the relatively high values of the color quality scale (CQS), color purity and absorption strength. The specific red line emission seen in K_2SiF_6:Mn^{4+} around 630 nm is caused by 3d3–3d3 transitions in Mn4+. The 3d3 electron configuration of Mn4+ results in 120 possible distributions of the three electrons over the ten available single-particle states of the 3d shell. The electronic Coulomb repulsion gives rise to a splitting of the 120-fold degenerate configuration in eight *LS* terms that can be found for the free Mn4+ ion, the magnitude of this splitting is characterized by the Racah parameters *B* and *C*. Because of these advantages, the red-emitting K_2SiF_6:Mn^{4+} conversion phosphor is chosen for enhancing the color quality of the 7000K Conformal Packaging MCW-LEDs [5-7].

In this research, the red-emitting K_2SiF_6:Mn^{4+} phosphor is proposed to enhancing the color quality of the 7000K conformal packaging MCW-LEDs. This paper can be divided into 3 section. The physical model of the 7000K conformal packaging MCW-LEDs were presented in the first section. In the second section, the mathematical optical description based on Mie theory of red-emitting K_2SiF_6:Mn^{4+} phosphor with Mat lab software and the simulation results with the commercial Light Tools software were collected. Finally, the research results were deeply discussed, analyzed, and investigated in the third sections and some conclusion was proposed. According to the results, we can conclude that the red-emitting $K_2SiF_6:Mn^{4+}$ conversion phosphor's size crucial influenced on the color quality of the 7000K conformal packaging MCW-LEDs. The red-emitting $K_2SiF_6:Mn^{4+}$ conversion phosphor could be considered as a prospective solution for MCW-LEDs improvement.

2. Research Method

The simulation comprises the setup of the 7000 K conformal packaging MCW-LEDs. In this situation, we use the real-world model of MCW-LEDs (Fig. 1(a)). In this simulation stage, we set the main parameters of the in-cup MCW-LEDs like below:

1) The depth, the inner and outer radius of the reflector to 2.07 mm, 8 mm and 9.85 mm, respectively.

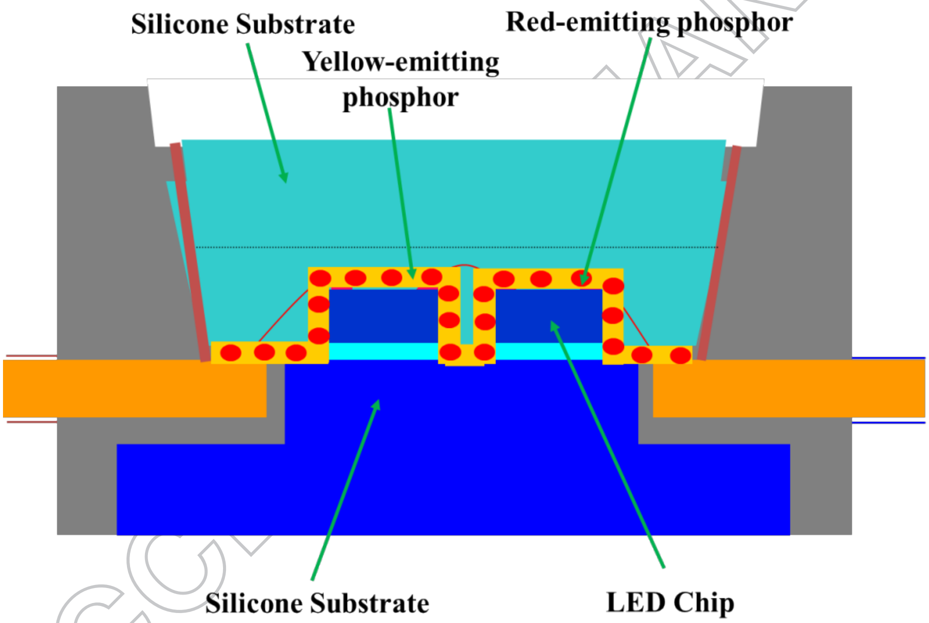
2) Four LED chips are covered with a fixed thickness of 0.08 mm and 2.07 mm. Each blue chip has a dimension of 1.14 mm by 0.15mm, the radiant flux of 1.16 W, and the peak wavelength of 453 nm (Fig. 1(b)).

In this simulation, the phosphor layer consist of the yellow-emitting YAG:Ce and the red-emitting $K_2SiF_6:Mn^{4+}$ conversion phosphors particles and the silicone glue, which respectively have the refractive indices of 1.85, 1.95 and 1.50. Also, the average radius of the yellow-emitting YAG:Ce phosphor particles are set to 7.25 μm like a value of real particle size. To make the color of MCW-LEDs produce the same when the concentration of the red-emitting $K_2SiF_6:Mn^{4+}$ phosphor varies, the yellow-emitting YAG:Ce phosphor concentration should be inversely changed to provide same correlated color temperature (CCT) value. The weight percentage of the MCW-LEDs phosphor layers can be expressed as:

$$\sum W_{pl} = W_{Yellow\ phosphor} + W_{silicone} + W_{Red\ phosphor} = 100\%$$

Here the $W_{silicone}$, $W_{Yellow\ phosphor}$ and $W_{Red\ phosphor}$ are in turn the weight percentage of the silicone glue, the yellow-emitting YAG: Ce phosphor and the red-emitting CeTb phosphors [15-17].

(a)



(b)

Fig.1. (a) The MCW-LED product of the Siliconware Precision Industries Co., Ltd., Taiwan, (b), Illustration of MCW-LEDs with the in-cup phosphor packaging.

The influence of the concentration of the red-emitting $K_2SiF_6:Mn^{4+}$ phosphor on the optical performance of the MCW-LEDs can be demonstrated using Mie theory [1, 3]. Here, we can apply Mie-scattering theory [18-26]. The scattering coefficient $\mu_{sca}(\lambda)$

(mm^{-1}), the absorption coefficient $\mu_{abs}(\lambda)$ (mm^{-1}), anisotropy factor $g(\lambda)$ (mm^{-1}), and reduced scattering coefficient $\delta_{sca}(\lambda)$ (mm^{-1}) can be computed by the below expressions (1), (2), (3), and (4):

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

$$\mu_{abs}(\lambda) = \int N(r) C_{abs}(\lambda, r) dr \quad (2)$$

$$g(\lambda) = 2\pi \int \int_{-1}^{1} p(\theta, \lambda, r) f(r) \cos\theta d \cos\theta dr \quad (3)$$

$$\delta_{sca} = \mu_{sca}(1 - g) \quad (4)$$

In these equations, $N(r)$ indicates the distribution density of diffusional particles (mm^3). C_{abs} and C_{sca} is the absorption and scattering cross sections (mm^2), $p(\theta,\lambda,r)$ is the phase function, λ is the light wavelength (nm), r is the radius of diffusional particles (µm), and θ is the scattering angle (°), and $f(r))$ is the size distribution function of the diffuser in the phosphorous layer. Moreover, $f(r)$ and $N(r)$ can be calculated by:

$$f(r) = f_{dif}(r) + f_{phos}(r) \quad (4)$$

$$N(r) = N_{dif}(r) + N_{phos}(r) = K_N.[f_{dif}(r) + f_{phos}(r)] \quad (5)$$

$N(r)$ is composed of the diffusive particle number density $N_{dif}(r)$ and the phosphor particle number density $N_{phos}(r)$. In these equations, $f_{dif}(r)$ and $f_{phos}(r)$ are the size distribution function data of the diffusor and phosphor particle. Here K_N is the number of the unit diffusor for one diffuser concentration and can be calculated by the following equation:

$$c = K_N \int M(r) dr \quad (6)$$

Where $M(r)$ *is* the mass distribution of the unit diffuser and can be proposed by the below equation:

$$M(r) = \frac{4}{3}\pi r^3 [\rho_{dif} f_{dif}(r) + \rho_{phos} f_{phos}(r)] \quad (7)$$

Here $\rho_{diff}(r)$ and $\rho_{phos}(r)$ are the density of diffuser and phosphor crystal.

3. Results and discussion

As displayed in Fig. 3, the scattering coefficients grew with increasing red phosphor concentration. It means that the white-light quality can be enhanced by controlling red phosphor concentration. The reduced scattering coefficient of red phosphor with wavelengths 453nm, 555nm and 680nm are the same each other's (Fig 4). It indicated that the scattering stability of red phosphor is used for controlling the color quality of MCW-LEDs. The results indicated that red phosphor particles had a significant advantage in producing blue light. The more the blue light emitted, the more the yellow ring phenomenon reduced. Fig. 5 show that the anisotropy coefficient is the same of the red and the blue light. However, the anisotropy coefficient of the yellow light is higher than others. Moreover, the scattering amplitude of the blue light is highest, and the scattering amplitude of the red light is lowest in comparison with each other (Fig. 6).

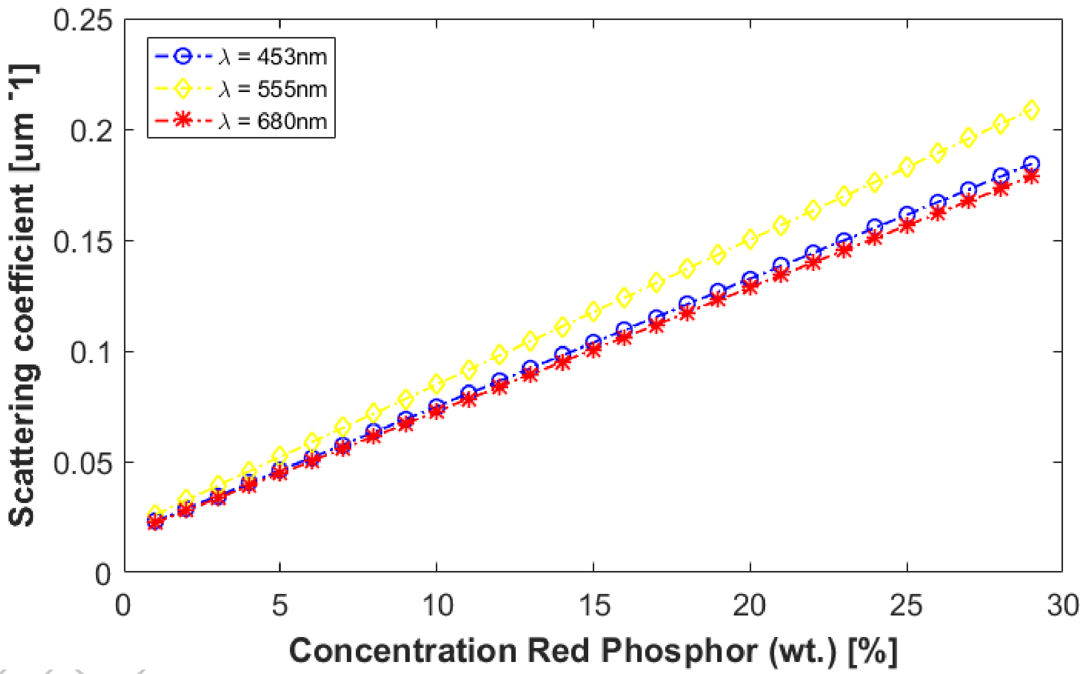


Fig. 3. Scattering coefficients of the red-emitting phosphor $Ba_2Si_5N_8Eu^{2+}$

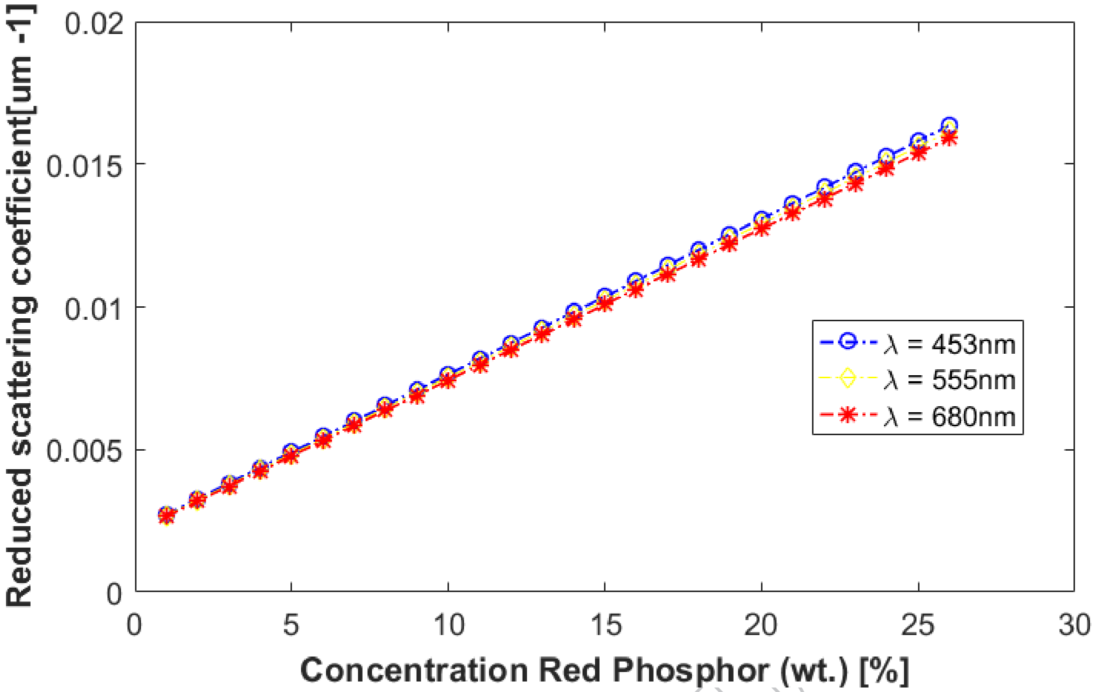


Fig. 4 Reduced scattering coefficient of the red-emitting phosphor $Ba_2Si_5N_8Eu^{2+}$ with wavelengths of 453nm, 555nm, and 680nm

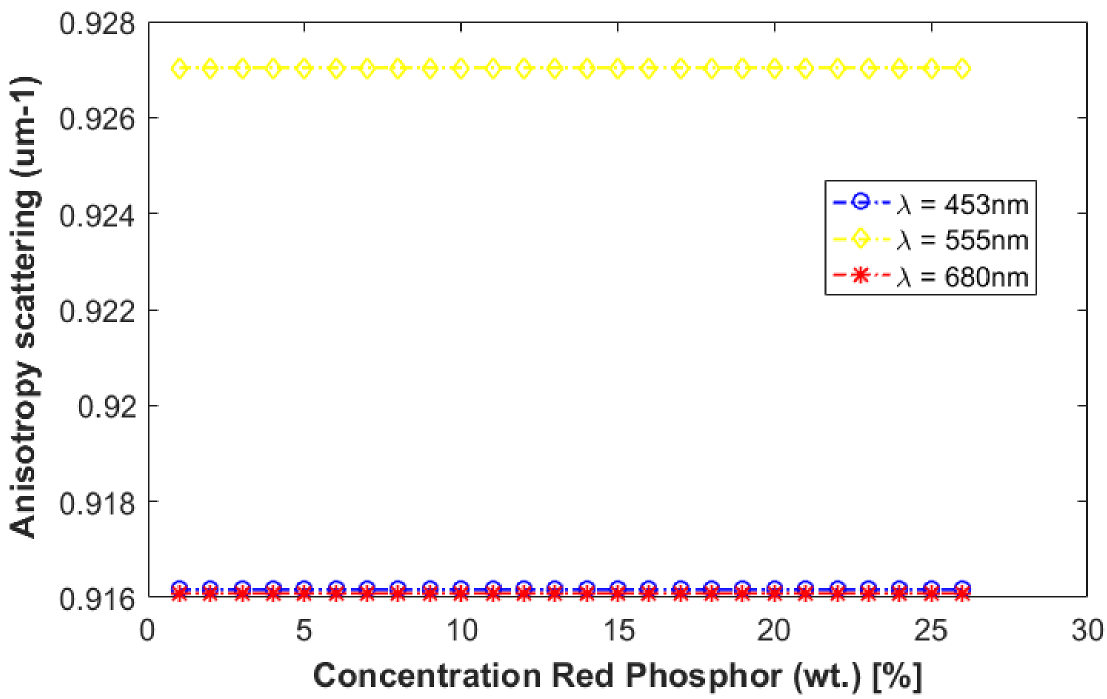


Fig. 5 Anisotropy coefficient of the red-emitting phosphor $Ba_2Si_5N_8Eu^{2+}$ with wavelengths of 453nm, 555nm, and 680nm

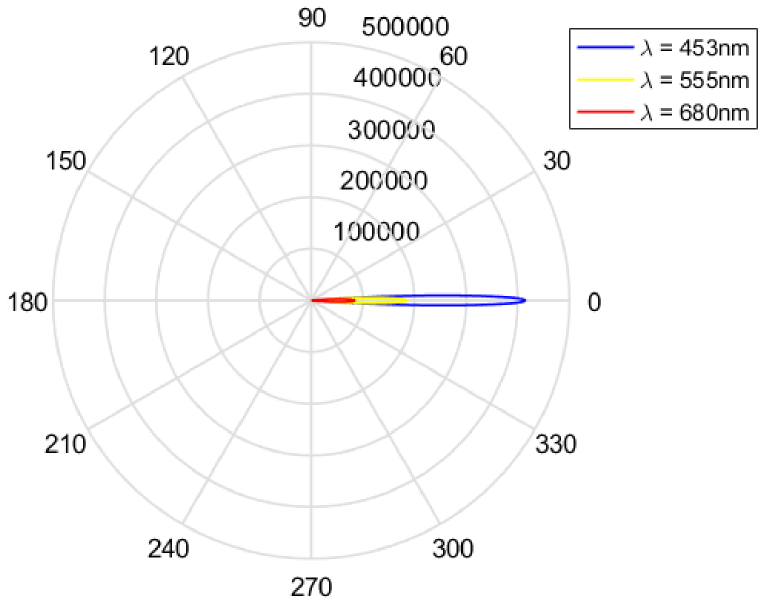


Fig. 6 The scattering amplitude of the red-emitting phosphor $Ba_2Si_5N_8Eu^{2+}$ with wavelengths of 453nm, 555nm, and 680nm

In this segment, the CRI, and CQS of the 7700K MCW-LEDs are calculated and obtained by using the commercial software Light Tools. In this simulation, the size of the red-emitting $K_2SiF_6:Mn^{4+}$ phosphor varied continuously from 1µm to 10µm. From the simulation results, Fig. 7 and 8 show the CQS and CRI of the 7000K conformal packaging MCW-LEDs while the size of the red phosphor changed from 1µm to 10µm. It can be indicated that the CQS and CRI grow crucially with the size of red phosphor in the range from 1µm to 6 µm The highest CQS and CRI is obtained with the red weight vary from 4µm to 6µm As shown in Fig. 7 and 8, the CQS and CRI could be obtained highest value near 67 and 69, respectively. From that point of view, the CQS, and CRI, of high CCT MCW-LEDs can be controlled by adding red-emitting $K_2SiF_6:Mn^{4+}$ phosphor in phosphor compound and varying its size.

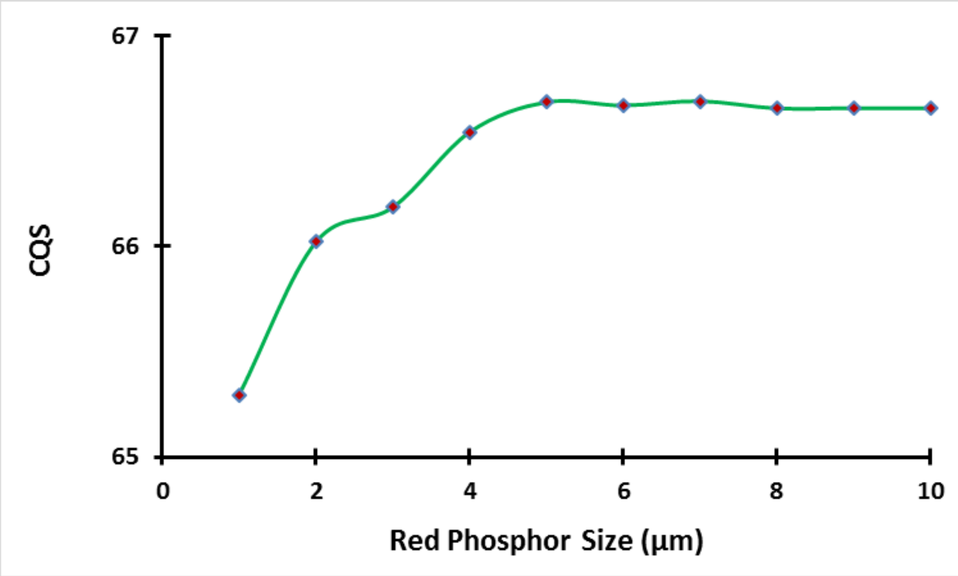


Fig. 7: The color quality scale (CQS).

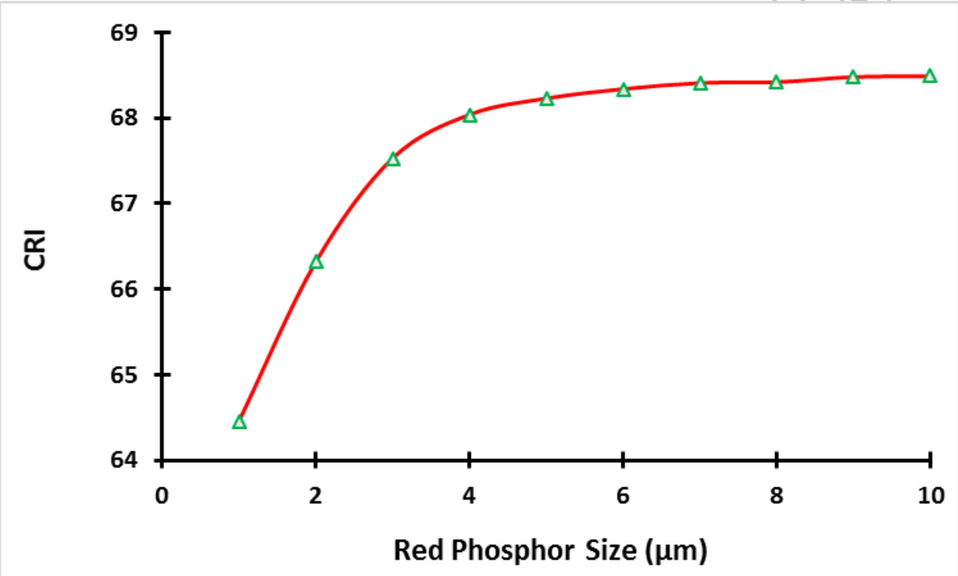


Fig. 8: The color rendering index (CRI).

4. Conclusion

The purpose of the current paper was to determine the influence of the red-emitting $K_2SiF_6:Mn^{4+}$ conversion phosphor's size on the color quality of the 7000K conformal packaging MCW-LEDs. The results of this investigation show that the size of the red $K_2SiF_6:Mn^{4+}$phosphor particles crucial influenced on the color quality of the MCW-LEDs. The both CRI, and CQS can obtain the best value at the 4μm to 6μm size of the red-emitting $K_2SiF_6:Mn^{4+}$ conversion phosphor. Further studies need to be carried out to validate the influence of the red-emitting $K_2SiF_6:Mn^{4+}$ phosphor's concentration on the optical performance of the conformal packaging MCW-LEDs.

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PUBLIC INTEREST STATEMENT

Light-emitting diodes (LEDs) have found their way into many applications in daily life, from warm-white LEDs for energy-efficient lighting to display backlights for smartphones, tablets, and televisions. The current attention to energy saving and reduction of CO2 emission in the atmosphere should, therefore, give an additional boost to the development of LEDs for lighting. In this research, we investigated the influence of the red-emitting K2SiF6:Mn4+ conversion phosphor on the color quality of the 7000K conformal packaging multi-chip white LEDs (MCW-LEDs). The research results indicated that the color quality of MCW-LEDs was crucially affected by the red-emitting K2SiF6:Mn4+ conversion phosphor's size. This research demonstrated a significant recommendation for selecting and developing the phosphor materials for MCW-LEDs manufacturing.

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