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$K_2SiF_6:Mn^{4+}$ PHOSPHOR: A NOVEL SOLUTION FOR IMPROVING THE COLOR PROPERTIES OF THE 5600K CPW-LEDs

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High-power white light-emitting diodes (LEDs) have attracted much attention due to their versatility in a variety of applications and growing demand in markets such as general lighting, automotive lamps, communications devices, and medical devices. In this paper, the effect of the red-emitting $K_2SiF_6:Mn^{4+}$ phosphor concentration on the color properties of the 5600K conformal packaging white LEDs (CPW-LEDs) is investigated. The research results are demonstrated based on Mie Theory by Mat Lab and Light Tools software. From the research results, we can see that the concentration of the red phosphor is significantly influenced on the CCT Deviation (CCT-D), Color rendering index (CRI), Color quality scale (CQS), and lumen output (LO) of the 5600K CPW-LEDs. This research can be proposed a novel recommendation for selecting and developing the phosphor materials for LEDs manufacturing.

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Keywords: Red-emitting phosphor, CPW-LEDs, Color properties, CQS, CRI.

1. Introduction

Nowadays, LEDs is popularly used in all areas such as LCD backlights, displays, transportation equipment lighting, and general lighting. LEDs are used as a light source for LCD backlights in products such as mobile phones, cameras, portable media players, notebooks, monitors, and TVs. Display applications include LED electronic scoreboards, outdoor billboards, and signage lightings, such as LED strips and lighting bars. Examples of transportation equipment lighting areas are passenger vehicle and train lighting (e.g., meter backlights, tail and brake lights), and ship and airplane lighting (e.g., flight error lighting and searchlights). General lighting applications are divided into indoor lighting (e.g., LED lighting bulbs, desk lighting, and surface lighting), outdoor lighting (e.g., decorative lighting, street/bridge lighting, and stadium lighting), and special lighting (e.g., elevator lighting and appliance lighting). The use of LEDs in general lighting has increased, beginning with street lighting in public areas and moving onto commercial/business lighting and consumer applications [1-4]. Thickness and concentration of phosphor are considered as the main factors in the white LEDs packaging. In previous studies, [8,9] in investigated the influence of thickness and concentration of the phosphor layer on the optical properties of WLEDs. In addition, the size, and concentration of the phosphor layer on the spatial color distribution (SCD) of WLEDs is proposed and investigated in [10]. Moreover, the influence of phosphor layer located on the optical properties of WLEDs is presented in [11-14]. In [15-17], novel recommendation for improving the optical performance of WLEDs by adding green or red phosphor into the phosphor layer.

In this paper, we propose and investigate the influence of the concentration of the red-emitting $K_2SiF_6:Mn^{4+}$ phosphor particle on the color properties in term of the color quality

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scale (CQS), color rendering index (CRI), CCT deviation (D-CCT) and the lumen output (LO) of the 5600K conformal packaging W-LEDs (CPW-LEDs). The results show that the concentration of the red phosphor in the phosphor layer significantly influenced on the optical properties of the CPW-LEDs. The main contributions of this research can be summarized as the followings:

1) The simulation model of 5600 K CPW-LEDs is conducted by Light Tools software.
2) The mathematical and simulation analysis of the scattering process in the phosphor layer is analyzed by Mat Lab software.
3) The influence of the $K_2SiF_6:Mn^{4+}$ phosphor concentration on CQS, CRI, D-CCT, and LO is demonstrated.

The remaining of this paper can be organized as follows. The physical model of the CPW-LEDs and the mathematical model of the scattering process are proposed in the second section. The results and some discussion is proposed in the third section. Finally, the fourth section concludes the research.

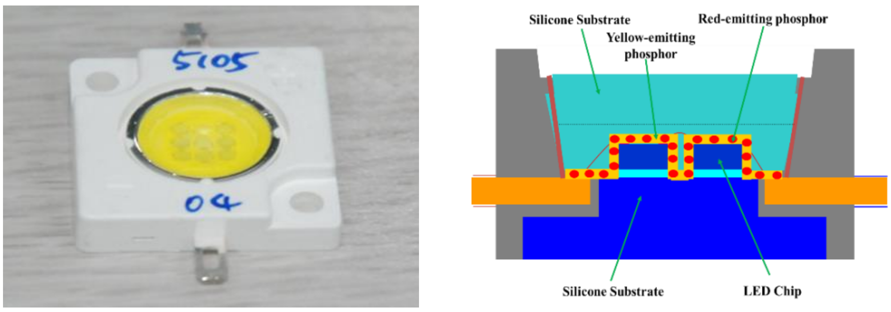
2. Research method

In this section, the real model of CPW-LEDs as shown in Fig. 1(a) is used to simulate the physical model of the 5600 K CPW-LEDs with the main parameters as the followings:

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)).

3) 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 [15-17].



(a) *(b)*

Fig. 1. (a) The real CPW-LEDs,
(b) The physical model of the CPW-LEDs.

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 the 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):

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

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

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

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

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(θ,λ,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:

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

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

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:

$$c = K_N \int M(r) dr \tag{6}$$

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

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

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

3. Results and discussion

From the mathematical description, we can see that the scattering coefficient of wavelengths 453nm, 555nm and 680nm increased when the concentration of the red phosphor varied from 4% to 24% as shown in Fig. 3. We can see that the red phosphor concentration crucially affected the optical properties of the white light. In the same way, Fig. 4 shows that the reduced scattering coefficient of the red phosphor is the same with wavelengths 453nm, 555nm, and 680nm in the increasing of the concentration of the red phosphor from 4% to 24%. Also, the anisotropy coefficient is presented in Fig. 5 with the concentration of the red phosphor varies from 4% to 24%. Finally, the connection between the scattering amplitude and the red phosphor concentration is proposed in Fig. 6. From the results, we can conclude that the red phosphor significantly influenced on the blue and yellow light of the CPW-LEDs.

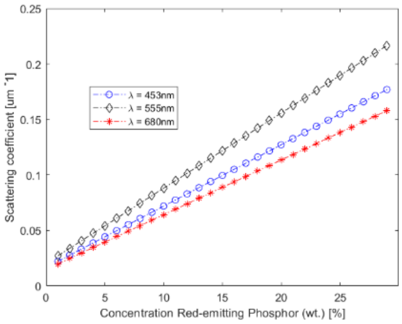


Fig. 3. Scattering coefficients of the red phosphor.

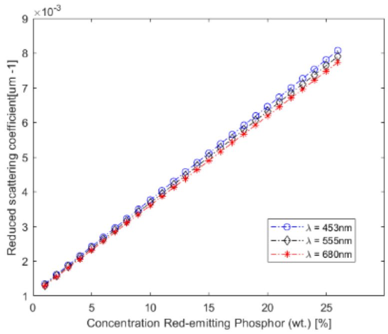


Fig. 4. Reduced scattering coefficient of the red phosphor.

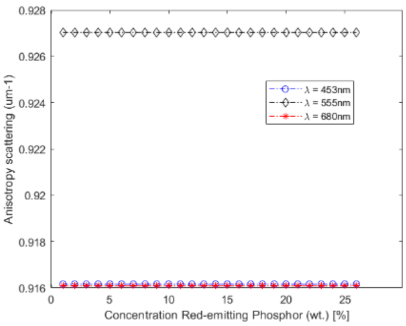


Fig. 5. Anisotropy coefficient of the red phosphor.

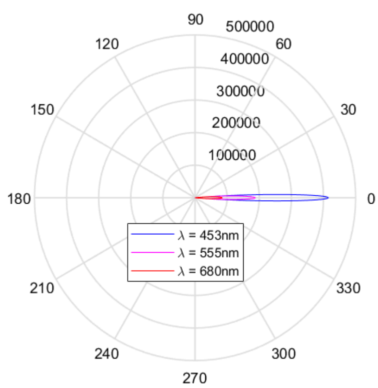


Fig. 6. The scattering amplitude of red phosphor.

In this section, we investigate the influence of the concentration of the red phosphor on the CQS, CRI, D-CCT and lumen output (LO) of the 5600 K CPW-LEDs by Light Tools software. As displayed in Fig. 7, CQS rises when the concentration of the red phosphor varies from 4% to 14% and then had a decrease after that value. The optimal value of CQS is near 62 with 14% concentration of the red phosphor. In the same direction, Lo of the CPW-LEDs increases significantly with the increasing the concentration of the red phosphor. The maximum value of LO can be obtained at 24% concentration of the red phosphor. However, CRI and D-CCT of the CPW-LEDs decrease while the concentration of the red phosphor increases from 4% to 24%. The optimal value of D-CCT can be proposed at 24% concentration of the red phosphor.

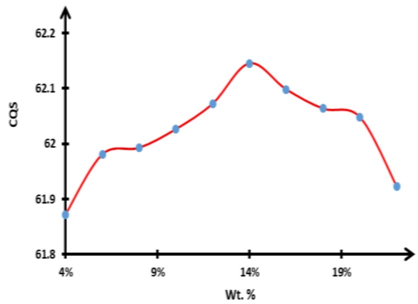


Fig. 7. CQS of CPW-LEDs.

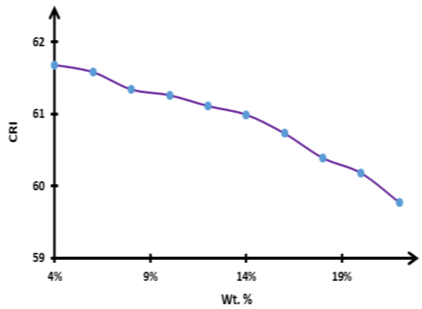


Fig. 8. CRI of CPW-LEDs.

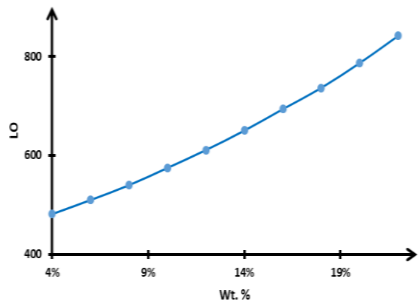


Fig. 9: LO of CPW-LEDs.

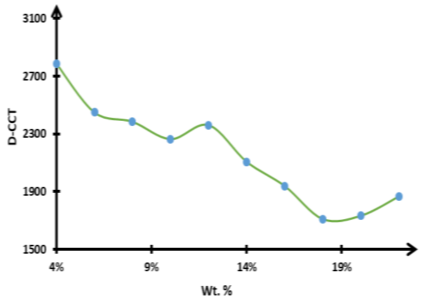


Fig. 10. D-CCT of CPW-LEDs.

4. Conclusion

In this paper, we introduce the new solution for improving the color properties of the 5600K CPW-LEDs by the red-emitting $K_2SiF_6:Mn^{4+}$ phosphor. It is observed that the concentration of the red phosphor crucially effected on the CRI, CQS, LO, and D-CCT of the 5600K CPW-LEDs. We can see that the optimal value of CQS is near 62 with 14% concentration of the red phosphor. The maximum value of LO can be obtained at 24% concentration of the red phosphor. The optimal value of D-CCT can be proposed at 24% concentration of the red phosphor. From the research results, we can conclude that the red $K_2SiF_6:Mn^{4+}$ phosphor is the novel solution for improving the color properties of the 5600K CPW-LEDs by the red-emitting $K_2SiF_6:Mn^{4+}$ phosphor.

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References

[1] LED Packaging for Lighting Applications, Design of LED Packaging Applications, 215 (2011), doi:10.1002/9780470827857, ch. 6.
[2] E. Gibney, Nature **514**(7521), 152 (2014), doi:10.1038/514152a.
[3] W. Holger, Q. Trinh, P. Bodrogi, T. Q. Khanh, LED Lighting: Technology and Perception, Weinheim, Wiley-VCH, 2015.
[4] Luo Xiaobing, Run Hu, Sheng Liu, Kai Wang, Progress in Energy and Combustion Science **56**, 1 (2016), doi:10.1016/j.pecs.2016.05.003.
[5] H. F. Sijbom, R. Verstraete, J. J. Joos, JD. Poelman, P. F. Smet, Optical Materials Express, **7**(9), 3332 (2017), doi:10.1364/ome.7.003332.
[6] P. F. Smet, A. B. Parmentier, D. Poelman, Journal of the Electrochemical Society **158**(6), 2011, doi:10.1149/1.3568524
[7] Y. Wang, H. Li, R. Zhang, M. Zhan, J. Zhang, RSC Adv. **5**(4), 2689 (2015), doi:10.1039/c4ra11198b
[8] T. N. Tran, Nguyen, F. G. Shi, Journal of Lightwave Technology **26**(21), 3556 (2008). doi:10.1109/jlt.2008.917087.
[9] Y. Shuai, Y. He, N. T. Tran, F. G.Shi, IEEE Photonics Technology Letters **23**(3), 137 (2011), doi: 10.1109/LPT.2010.2092759.
[10] C. Sommer, F.-P. Wenzl, P. Hartmann, P. Pachler, M. Schweighart, S. Tasch, G. Leising, IEEE Photonics Technology Letters **20**(9), 739 (2008), doi:10.1109/lpt.2008.921063.

[11] Tin P. T., Khanh Nhan N. H., Tran M., Tran T. T., Digest Journal of Nanomaterials and Biostructures **13**(4), 1027 (2019).
[12]Liu Zongyuan, Sheng Liu, Kai Wang, Xiaobing Luo, Analysis of Factors Affecting Color Distribution of White LEDs, 2008 International Conference on Electronic Packaging Technology& High Density Packaging. doi:10.1109/icept.2008.4607013.
[13]Liu Zongyuan, Sheng Liu, Kai Wang, Xiaobing Luo, IEEE Photonics Technology Letters **20**(24), 2027 (2008), doi:10.1109/lpt.2008.2005998.
[14] Liu Zongyuan, Sheng Liu, Kai Wang, Xiaobing Luo, Effects of Phosphor'sLocation on LED Packaging Performance, 2008, International Conference on Electronic Packaging Technology & High Density Packaging, doi:10.1109/icept.2008.4606982.
[15]Minh Tran Hoang Quang, Nguyen Huu Khanh Nhan, Nguyen Doan Quoc Anh, Hsiao-Yi Lee, Journal of the Chinese Institute of Engineers **40**(4), 313 (2017), doi:10.1080/02533839.2017.1318720.
[16] Anh Nguyen Doan Quoc, Hsiao-Yi Lee, Tran Thanh Phuong, Nguyen Huu Khanh Nhan, Tran Hoang Quang Minh, Truong Huu Ly, Journal of the Chinese Institute of Engineers **40**(3), 228 (2017), doi:10.1080/02533839.2017.1299592.
[17] Phu Tran Tin; Tran Hoang Quang Minh; Nguyen Huu Khanh Nhan, Tan N. Nguyen, Materials Science-Poland **36**(4), 563 (2018), doi: 10.2478/msp-2018-0095.
[18] Optical Properties of Nanoparticle Systems, Beyond Mie's Theory II - The Generalized Mie Theory, 317 (2011), doi:10.1002/9783527633135.ch10.
[19] F. Jeppe Revall, N. Jørgen Christensen, H. Wann Jensen, Predicting the Appearance of Materials Using Lorenz–Mie Theory, The Mie Theory Springer Series in Optical Sciences, 101 (2012), doi:10.1007/978-3-642-28738-1_4.
[20] D. Mackowski, The Extension of Mie Theory to Multiple Spheres, The Mie Theory Springer Series in Optical Sciences, 223 (2012), doi:10.1007/978-3-642-28738-1_8.
[21] T. Wriedt, Mie Theory: A Review, The Mie Theory Springer Series in Optical Sciences, 53 (2012), doi:10.1007/978-3-642-28738-1_2.
[22] X. Luo, R. Hu, Chip packaging: Encapsulation of nitride LEDs. Nitride Semiconductor Light-Emitting Diodes (LEDs), 441 (2014). doi:10.1533/9780857099303.2.441
[23] Nhan, N. H. Khanh; Minh, T. H. Quang; Nguyen, T. N., Journal of Ovonic Research **13**(6), 325(2017).
[24] Zhong Jiajian, Mingyuan Xie, Zhigui Ou, Rui Zhang, Min Huang, Fuli Zhao, Mie Theory Simulation of the Effect on Light Extraction by 2-D Nanostructure Fabrication, 2011, Symposium on Photonics and Optoelectronics (SOPO), doi:10.1109/sopo.2011.5780566.
[25] Phu Tran Tin; Nguyen Huu Khanh Nhan; Tran Hoang Quang Minh, Tan N. Nguyen, Proceedings of the Estonian Academy of Sciences **67**(4), 337 (2018). doi: 10.3176/proc.2018.4.06.
[26] Nguyen Huu Khanh Nhan; Tran Hoang Quang Minh; Nguyen, Tan N. Nguyen, Current Optics and Photonics **1**(6), 613 (2017), doi: 10.3807/COPP.2017.1.6.613.