Using Sr[Mg3SiN4]Eu2+ phosphor for enhancing color uniformity and luminous efficacy of the 7000 K IPP-WLEDs

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ABSTRACT

In this paper, we built the simulation model of the 7000 K in-cup phosphor packaging white LEDs (IPP-WLEDs) by using the Light Tools software. After that, the effect of the Sr[Mg3SiN4]Eu2+ phosphor particle’s size on the lighting performance in term of CCT Deviation (D-CCT), Color Rendering Index (CRI), Color Quality Scale (CQS), and Lumen Output (LO) is investigated. Moreover, the scattering processes in the phosphor layers of the 7000 K IPP-WLEDs is derived using Mat Lab software. From the research results, we can state that the phosphor size significantly affects the lighting performance of the 7000K IPP_WLEDs.

Keywords:
CQS
CRI
IPP-WLEDs
Mie theory
Sr[Mg3SiN4]Eu2+ phosphor

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1. INTRODUCTION

Light-emitting diodes (LEDs) using semiconductors offer an alternative method of illumination. The operation of LEDs is based on spontaneous light emission in semiconductors, which is due to the radiative recombination of excess electrons and holes [1-6] that are produced by the injection of current with small energy losses. As a result, compared with conventional lamps, LED-based light sources have a superior lifetime, efficiency, and reliability, which promise significant reductions in power consumption and pollution from fossil fuel power plants [1-6]. LEDs is a solid-state light source which emits white light based on a blue die covered by the yellow or green-red phosphor. Such a light source has been intensively applied to general lighting and replaced most light sources in general lighting and even in special lighting (automobiles, transportation, communication, imaging, agriculture, and medicine) owing to its many advantages [3-5], sources shortly [6-8].

Although there are lots of issues needed to be addressed in white LEDs, such as chip processing, light extraction efficiency, heat sink structures, resin materials, reliability, life test, etc., this paper focuses on phosphors materials and their applications in white LED packaging. Phosphor coating is the most critical fluid flow problem in LED packaging since the coating process determines the phosphor thickness, location, distribution, and morphology in LED packaging. Moreover, changing the phosphor location will affect the LEE and CCT of LEDs. Phosphor thickness and concentration are the second consideration in LEDs because
the luminous flux and color of LEDs are adjusted mainly through changing the thickness and concentration. Thickness and concentration can be varied in manufacturing and will, therefore, affect the optical consistency of LEDs [9-15].

As a novel class of inorganic phosphors, oxynitride and nitride luminescent materials have received considerable attention because of their potential applications in solid-state lightings and displays. In this paper, we built the simulation model of the 7000 K in-cup phosphor packaging white LEDs (IPP-WLEDs) by using the Light Tools software. After that, the effect of the Sr[Mg3SiN4]Eu2+ phosphor particle’s size on the lighting performance in term of CCT Deviation (D-CCT), Color Rendering Index (CRI), Color Quality Scale (CQS), and Lumen Output (LO) is analyzed and investigated. Also, the scattering processes in the phosphor layers of the 7000 K IPP-WLEDs is derived using Mat Lab software. From the research results, we can state that the phosphor size significantly affects the lighting performance of the 7000K IPP-WLEDs.

2. RESEARCH METHOD
2.1. Simulation Model

In this section, the in-cup packaging WLEDs is simulated by using the commercial Light Tools software based on the Monte Carlo ray-tracing method (Figure 1). In this physical model of WLEDs, the basic parameters of the in-cup packaging WLEDs are defined as below:

a) The reflector: 8 mm bottom length, a 2.07 mm height, and a 9.85 mm length.
b) The in-cup phosphor layer: the thickness of 0.08 mm covers the 9 LED chips.
c) The LED chip: 1.14 mm square base and a 0.15 mm height. The radiant flux of each blue chip is 1.16 W at wavelength 455 nm.

![Figure 1. The 7000K IPP-WLEDs physical structure](image)

2.2. Mathematical Analysis

In this section, applying Mie theory [16-18, 21-25], the coefficients of the scattering process of the phosphor layer of the in-cup packaging WLEDs can be calculated as the below expressions:

A. The scattering coefficient $\mu_{sc}(\lambda)$:

$$
\mu_{sc}(\lambda) = \int N(r)C_{sc}(\lambda, r)dr
$$

Where $N(r)$ (mm$^3$) is the distribution density of diffusional particles. $N(r)$ is composed of the diffusive particle number density $N_{dif}(r)$, and the phosphor particle number density $N_{phos}(r)$ can be presented as:

$$
N(r) = N_{dif}(r) + N_{phos}(r) = K_{p}[f_{dif}(r) + f_{phos}(r)]
$$

Moreover, $C_{sc}$ (mm$^2$) is the scattering cross-sections. In Mie theory, $C_{sc}$ can be obtained by the following expression:

$$
C_{sc} = \frac{2\pi}{k^2} \sum_{n=0}^{\infty} (2n-1)(|a_n|^2 + |b_n|^2)
$$
Here \( \lambda \) (nm) is the light wavelength, and \( r \) (µm) is the radius of diffusional particles.

B. The anisotropy factor \( g(\lambda) \),

\[
g(\lambda) = 2\pi \int_{-1}^{1} p(\theta, \lambda, r) f(r) \cos \theta d\theta \cos \theta dr
\]

Where \( p(\theta, \lambda, r) \) is the phase function, \( f(r) \) is the size distribution function of the diffuser in the phosphor layer, \( \theta \) (°) is the scattering angle.

C. The reduced scattering coefficient \( \delta_{\text{sca}}(\lambda) \):

\[
\delta_{\text{sca}} = \mu_{\text{sca}}(1 - g)
\]

In these equations, \( f(r) \) and \( N(r) \) can be calculated by:

\[
f(r) = f_{\text{dif}}(r) + f_{\text{phos}}(r)
\]

Where \( f_{\text{dif}}(r) \) and \( f_{\text{phos}}(r) \) are the size distribution function data of the diffusor and phosphor particle.

3. NUMERICAL RESULTS AND DISCUSSION

In Figure 2, the scattering coefficient (SC) of the red phosphor crucial grew with increasing the red phosphor’s size. The red phosphor has an excellent absorption ability for the blue light from LEDs. On another hand, the reduced scattering coefficient (RSC) of the red phosphor is the same with each other in depending on the concentration (Figure 3). It indicated that the scattering stability of the red phosphor showed great uses for controlling the color quality of the in-cup packaging WLEDs. From the analysis the scattering process in the phosphor layer of the in-cup packaging WLEDs, the results indicated that the involvement of the red phosphor into the phosphor compounding could play a major role in controlling the optical properties of the in-cup packaging WLEDs [16-18].

![Figure 2. The scattering coefficient (SC)](image)

![Figure 3. The reduced scattering coefficient (RSC)](image)

Furthermore, the effect of the red phosphor size on the CRI and CQS of the 7000KIPP-WLEDs are drawn in Figure 6 and 7. In these cases, we set the size of the red phosphor from 4 µm to 10 µm. From the research results, we can see that the CRIRises from 52to 66 and the CQSincreases from 57 to 65 with the rising the red phosphor size, respectively. This effect can be caused by the more scattering processes in the phosphor layer, which leads to increasing the color quality of the IPP-WLEDs.
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4. CONCLUSION

In this paper, we built the simulation model of the 7000 K in-cup phosphor packaging white LEDs (IPP-WLEDs) by using the Light Tools software. After that, the effect of the Sr[Mg3SiN4]Eu2+ phosphor particle’s size on the lighting performance in term of CCT Deviation (D-CCT), Color Rendering Index (CRI), Color Quality Scale (CQS), and Lumen Output (LO) is analyzed and investigated. Besides, the scattering processes in the phosphor layers of the 7000 K IPP-WLEDs is derived using Mat Lab software. From the research results, we can state that the phosphor size significantly affects the lighting performance of the 7000K IPP-WLEDs.

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REFERENCES

[1] LED Packaging for Lighting Applications. 2011. “Design of LED Packaging Applications,” 215–315. doi:10.1002/9780470827857.ch6.

[2] Gibney, Elizabeth. 2014. “Nobel for Blue LED That Revolutionized Lighting.” Nature 514 (7521): 152–153. doi:10.1038/514152a.

[3] Liu, Zong-Yuan, Sheng Liu, Kai Wang, and Xiao-Bing Luo. 2010. “Studies on Optical Consistency of White LEDs Affected by Phosphor Thickness and Concentration Using Optical Simulation.” IEEE Transactions on Components and Packaging Technologies 33 (4): 680–687. doi:10.1109/tcapt.2010.2044576.

[4] Luo, X., & Hu, R. (2014). Chip packaging: Encapsulation of nitride LEDs. Nitride Semiconductor Light-Emitting Diodes (LEDs), 441-481. doi:10.1533/9780857099303.2.441

[5] Luo, Xiaobing, Run Hu, Sheng Liu, and Kai Wang. 2016. “Heat and Fluid Flow in High-Power LED Packaging and Applications.” Progress in Energy and Combustion Science 56: 1–32. doi:10.1016/j.pecs.2016.05.003.

[6] Seong, Tae-Yeon. 2013. III-Nitride Based Light Emitting Diodes and Applications. Dordrecht: Springer Science & Business Media.

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[7] Xie, Rong-Jun, and Naoto Hiroasaki. 2007. “Silicon-Based Oxynitride and Nitride Phosphors for White LEDs—A Review”. Science and Technology of Advanced Materials 8 (7-8), 588-600. https://doi.org/10.1016/j.stam.2007.08.005.

[8] Shuai, Y. Y. He, N. T. Tran, F. G. Shi, 2011, Angular CCT uniformity of phosphor-converted white LEDs: effects of phosphor materials and packaging structures, IEEE Photonics Technology Letters 23(3): 137–139, doi: 10.1109/LPT.2010.2092759.

[9] Fu, Xing, Huai Zheng, Sheng Liu, and Xiaobing Luo. 2012. “Effects of Packaging Structure on Optical Performances of Phosphor Converted Light Emitting Diodes.” Frontiers of Optoelectronics 5 (2): 153–156. doi:10.1007/s12200-012-0254-1.

[10] Yu, Renyong, Shangzhong Jin, Songyuan Cen, and Pei Liang. 2010. “Effect of the Phosphor Geometry on the Luminous Flux of Phosphor-Converted Light Emitting Diodes.” IEEE Photonics Technology Letters 22 (23): 1765–1767. doi:10.1109/LPT.2010.2085080.

[11] Joo, Byung-Yun, and Jae-Hyeon Ko. 2013. “Analysis of Color Uniformity of White LED Lens Packages for Direct-Lit LCD Backlight Applications”. Journal of the Optical Society of Korea 17 (6), 506-12. https://doi.org/10.3807/josk.2013.17.6.506.

[12] Sun, Wen-Shing, Chuen-Lin Tien, Jui-Wen Pan, Tsung-Hsun Yang, Chih-Hsuan Tsuei, and Yi-Han Huang. 2013. “Simulation and Comparison of the Lighting Efficiency for Household Illumination With LEDs and Fluorescent Lamps”. Journal of the Optical Society of Korea 17 (5), 376-83. https://doi.org/10.3807/josk.2013.17.5.376.

[13] Oh, Ji Bye, Yun Jae Eo, Su Ji Yang, and Young Rag Do. 2015. “High-Quality Multipackaged Phosphor-Converted LEDs for Yellow Photolithography Room Lamp”. IEEE Photonics J. 7 (2), 1-8. https://doi.org/10.1109/jphoton.2015.2415674.

[14] Chen, Yu, Minhao Zhang, and Guoxing He. 2013. “Comments on ‘Maximum White Luminous Efficacy of Versus Color Rendering Index and Color Temperature: Exact Results and a Useful Analytic Expression’”. J. Display Technol. 9 (10), 859-60. https://doi.org/10.1016/j.jdt.2013.2279275.

[15] Schratz, Michael, Christine Gupta, TJ Struhs, and Kara Gray. 2013. “Reducing Energy and Maintenance Costs While Improving Light Quality and Reliability With Led Lighting Technology”, January. https://doi.org/10.1109/pptc.2013.6656043.

[16] Quang Minh, Tran Hoang, Nguyen Huu Khanh Nhan, Nguyen Doan Quoc Anh, and Hsiao-Yi Lee. 2017. “Red-Emitting α-SrO·3B2O3:Sm2+ Phosphor: An Innovative Application for Increasing Color Quality and Luminous Flux of Remote Phosphor White LEDs”. Journal of the Chinese Institute of Engineers 40 (4), 313-17. https://doi.org/10.1080/02533839.2017.1318720.

[17] Quoc Anh, Nguyen Doan, Hsiao-Yi Lee, Tran Thanh Phuong, Nguyen Huu Khanh Nhan, Tran Hoang Quang Minh, and Truong Huu Ly. 2017. “Y2O3:Eu3+ Phosphor: A Novel Solution for an Increase in Color Rendering Index of Multi-Chip White LED Packages”. Journal of the Chinese Institute of Engineers 40 (3), 228-34. https://doi.org/10.1080/02533839.2017.1299592.

[18] Minh, Tran Hoang Quang, Nguyen Huu Khanh Nhan, Nguyen Doan Quoc Anh, and Hsiao-Yi Lee. 2017. “Novel Lighting Properties of White LEDs With Two-Layered Remote Phosphor Package Using Red-Emitting α-SrO·3B2O3:Sm2+ Phosphor” 35 (3), 618-25. https://doi.org/10.1016/j.sop.2017-0071.

[19] O. Tapaninen, 2016, Optical and thermal simulation chain for LED package, 17th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE), Montpellier. doi:10.1109/EuroSimE.2016.7463349.

[20] Mishchenko, Michael I., Larry D. Travis, and Andrew A. Lacis, 2002. Scattering, Absorption, and Emission of Light by Small Particles. Cambridge:Cambridge University Press.

[21] Zhong, Jiujian, Mingyuan Xie, Zhigui Ou, Rui Zhang, Min Huang, and Fuli Zhao. 2011. “Mie Theory Simulation of the Effect on Light Extraction by 2-D Nanostucture Fabrication.” 2011 Symposium on Photonics and Optoelectronics (SOPO), doi:10.1109/sopo.2011.5780566.

[22] Jonasz, Miroslaw, and Georges R. Fournier. 2007. “General Features of Scattering of Light by Particles in Water.” Light Scattering by Particles in Water, 87–143. doi:10.1016/b978-012388751-1/50003-x.

[23] K. Pan, et al., “Study on Reliability and Lifetime Prediction of High Power LEDs,” Indonesian Journal of Electrical Engineering and Computer Science, vol/issue: 12.

[24] Peng H. Y., et al., “Red (SrCa)AlSiN3: Eu2+ Nitride Phosphor Particle Size of Phosphor Converted Warm White LEDs,” Indonesian Journal of Electrical Engineering and Computer Science, vol/issue: 12(7), 2014.

[25] Tran Tin, Pbu, Anh Vu Le, Minh Tran, Nguyen Huu Khanh Nhan, and Tran Thanh Trang, n.d. “Improving CCT-D and LO of the 6600K ICP-WLEDs by K2SiF6: Mn4+ Phosphor”. IJEPDS 10 (2), 1059. Accessed July 12, 2019. https://doi.org/10.11591/iypeds.v10.i2.pp1059-1063.