Increasing Optical Performance of 8500 K, 7000 K Remote-Packaging WLEDs by α-SrO$_3$B$_2$O$_3$:Sm^{2+} Conversion Phosphor

Huu Khanh Nhan NGUYEN, Hoang Quang Minh TRAN, Hsiao-Yi LEE

Optoelectronics Research Group, Faculty of Electrical and Electronics Engineering,
Ton Duc Thang University, Ho Chi Minh City, Vietnam

Corresponding Author: Hoang Quang Minh TRAN (email:tranhoangquangminh@tdt.edu.vn)
(Received: 14-December-2017; accepted: 04-March-2018; published: 31-March-2018)
DOI: http://dx.doi.org/10.25073/jaec.201821.86

Abstract. *In this paper, by mixing the α-SrO·3B$_2$O$_3$:Sm^{2+} conversion phosphor into the phosphor layer, an innovative recommendation for increasing optical performance of the white LEDs (WLEDs) with remote-packaging, which has an average correlated color temperature (CCT) of 7000K and 8500K, is proposed and demonstrated. By varying α-SrO·3B$_2$O$_3$:Sm^{2+} concentration from 2% to 24%, the obtained results proposed that color uniformity, color rendering index (CRI), color quality scale (CQS), and luminous efficacy could be improved significantly. The results demonstrated a prospective recommendation for manufacturing remote-packaging WLEDs.*

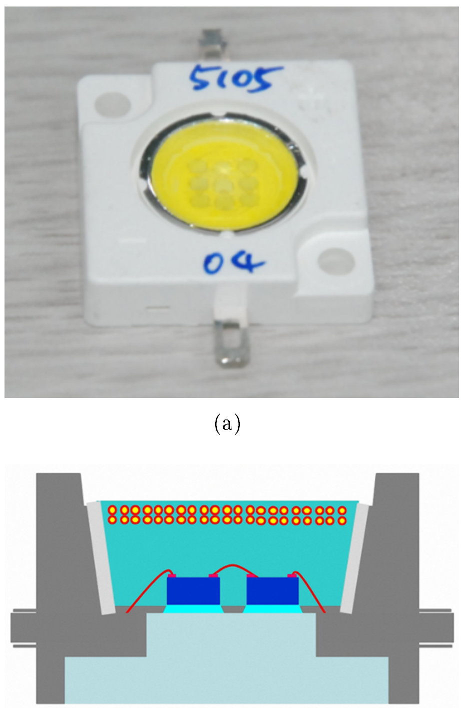
Key Words: ***Remote-packaging; α-SrO·3B$_2$O$_3$:Sm^{2+}; CCT Deviation; luminous efficacy.***

I. INTRODUCTION A lighting revolution is sweeping all over the world and is stealthily coming in and improving our everyday life. In comparison with fluorescent lamps and incandescent, the InGaN-based white-light-emitting diodes (LEDs) obtain so many advantages in energy efficiency, long lifetime, compactness, and environment-friendly and designable features. In the last decades, the efficiency of white LEDs lighting had already exceeded that of the incandescent lamps and was competitive with fluorescent lamps. Without a doubt, the white LEDs (WLEDs) lighting has been setting foot in the lighting industry and dramatically challenges the conventional lighting [1]-[3]. Industrial technology system of solid state lighting mainly includes four key technological fields: epitaxy material technology, chip design and manufacturing (upstream industry), packaging materials (midstream industry) and process technology and system integration technology and applications (downstream industry). Phosphor converted LEDs (pcLED) which combines a blue LEDs chip, and the yellow emitting phosphor is the most common approach to accomplish white light emission through LEDs packaging [4],[5]. In the last decades, many works have concentrated on increasing the optical performance of WLEDs in phosphor packaging direction. Tran el al. in [6],[7] proposed that the less phosphor concentration and the more phosphor thickness can be caused the higher luminous efficacy (lower trapping efficiency and fewer backs scattering of light) Moreover, the phosphor concentration, thickness, and size was influence on the spatial color distribution of WLEDs in [8]. The research results showed that the phosphor thickness, concentration and size can improve the spatial color uniformity of WLEDs. Furthermore, [9]-[12] was proposed and investigated the influence of phosphor location on the color uniformity of the WLEDs. It was clearly showed that the phosphor location in the phosphor layer significantly affected on the color uniformity. In the last few years, improvement of the optical performance of WLEDs by adding green or red phosphor into the phosphor compounding was investigated in [13]-[15]. From this point of view, improving the optical performance of MCW-LEDs by adding diffusers into the phosphor compounding is still necessary to investigate and we try to fill the remaining gap by this paper.

Red-emitting α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} phosphor having a peak wavelength of 680 nm, which is one of the red polycrystalline phosphors, is manufactured from three oxides including strontium oxide (SrO), samarium oxideSm_2O_3, and orthoboric acid (H_3BO_3). Sm^{2+} ions are added to the polycrystalline phosphor for enhancing its absorbability at the excitation spectrum region from 420 nm to 502 nm, resulting in higher luminous efficiency. Besides, with the advantages of excellent thermal and chemical stability, α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} can be used for compensation red-light, resulting in the enhancing of the color quality of LED lamps. However, until now, there have been too few studies which employ α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} for RP-WLEDs [13], [16]-[17].

In this work, an innovative method is proposed of mixing red-emitting α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} conversion phosphor into the yellow YAG:Ce phosphor compounding to improve the optical performance of the remote-packaging WLEDs. The influence of the α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} conversion phosphor particles' concentration on the optical performance of WLEDs is analyzed and demonstrated. This work can be divided into two main segments: 1) using the Light Tools software to simulate the physical model of the remote-packaging WLEDs. Then mixing α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} particles into the phosphor compounding of the WLEDs; 2) analyzing and investigating the effects of α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} concentration on the optical performance of WLEDs by results from Light Tools and Mat lab software. The research results indicated that CCT Deviation (D-CCT), Color rendering index (CRI), color quality scale (CQS), and lumen efficacy could be significantly increased by varying the concentration of α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} phosphor particles from 2% to 24%. Finally, the improvement of optical performance of WLEDs is demonstrated using Monte Carlo simulation and Mie-scattering theory.

II. SYSTEM MODEL In this study, the remote-packaging WLEDs having average CCTs of 8500 K, 7000 K are employed. The real system model of the remote-packaging WLEDs is presented in Figure 1a. From this real model, the remote-packaging WLEDs can be simulated by the Light Tools software in Figure 1(b). In this research, WLEDs have been commonly constructed like in previous studies. The reflector of WLED has an 8 mm bottom length, a 2.07 mm height, and a 9.85 mm length. Each LEDs chip with an area of 1.14 square millimeters and a 0.15 mm height is bound in the cavity of the reflector. The radiant flux of each blue chip is 1.16 W [13].



(a)

(b)

Fig. 1: (a) The real model WLEDs; (b) The simulation remote-packaging WLEDs.

In the simulation model Figure 1(b), the concentration of α-SrO$\cdot$3B$_2$O$_3$:Sm^{2+} should be increased from 2% to 24% for selecting an optimal concentration. In order to keep the average CCT values of the WLEDs, the concentration of the yellow YAG:Ce phosphor's concentration must be controlled. The optical performance of α-SrO·3B_2O_3:Sm^{2+} particles are configured by using the Light Tools software and investigated by applying Mie-theory and Monte Carlo method. In Mie-theoretical calculation, the average radius of two types of phosphor particles are selected at 7.25 μm. The refractive indexes of silicone glue, SiO_2, α-SrO·3B_2O_3:Sm^{2+}, and YAG:Ce particles are chosen at 1.5, 1.54, 1.80, and 1.83, respectively [13].

From the previous literatures, Mie-theory is popularly used for calculating scattering properties of particles [?]. In this work, the scattering properties of α-SrO·3B_2O_3:Sm^{2+} particles including the scattering coefficient $\mu_{scattering}(\lambda)$, anisotropy factor g($\lambda$), and reduced scattering coefficient $\delta_{sca}(\lambda)$ can be computed by equations (1), (2), and (3):

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

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

$$\delta_{scattering}(\lambda) = \mu_{scattering}(1 - g). \quad (3)$$

Where N(r) indicates the distribution density of particles (mm^{-3}), r is the radius of particles (*upmu*m), λ is the light wavelength (nm), θ is the scattering angle, $C_{scattering}$ is the scattering cross sections (mm^2), p(θ,λ,r) is the phase function, and f(r) is the size distribution function of α-SrO3B_2O_3:Sm^{2+} particles. In this equations, f(r), N(r), p(θ,λ,r) and $C_{scattering}$ can be calculated by the followings:

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

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

$$p(\theta, \lambda, r) = \frac{4\pi\beta(\theta, \lambda, r)}{k^2 C_{sca}(\lambda, r)} \quad (6)$$

$$C_{sca} = \frac{2\pi}{k^2} \sum_{0}^{\infty} (2n - 1)(|a_n|^2 + |b_n|^2) \quad (7)$$

Where k is the wavenumber ($2\pi/\lambda$), and a_n and b_n are the expansion coefficients.

As presented in Figure 2, the scattering coefficients grow with the α-SrO·3B_2O_3:Sm^{2+} concentration.

From the simulation, we can see that at 453 nm and 555 nm the scattering coefficients have the highest and lowest values, respectively. In this situation, the blue-light intensity becomes stronger than yellow-light. Moreover, the participation of α-SrO·3B_2O_3:Sm^{2+} particles can enhance the absorption ability of blue light. Here, the main role of α-SrO·3B_2O_3:Sm^{2+} particles is to increase red-light in WLEDs. From these reasons, α-SrO·3B_2O_3:Sm^{2+} should be considered for improving the optical performance of WLEDs.

Figure 3 presents the anisotropy factors ofα-SrO·3B_2O_3:Sm^{2+} particles at the wavelengths of 453 nm, 555 nm, and 680 nm, respectively. It is observed from the results that the anisotropy factor values at 555 nm are higher than those at 453 and 680 nm, which is an expected result. However, it is at 555nm that the maximum anisotropy factor value is obtained. This means that α-SrO·3B_2O_3:Sm^{2+} should display the strongest scattering event at 555 nm. Furthermore, the Monter Carlo simulation in Light Tools software can be produce for convincing the analysis. From simulation results, the anisotropy factors have a slight deviation approximately between 0.978 and 0.982. From the results, the color quality of the WLEDs can be enhanced by the varying scattering effect of the wavelengths.

In the Mie-scattering analysis section, the concentration of α-SrO·3B_2O_3:Sm^{2+} particles is varied from 0% to 50%, continuously. As illustrated in Figure 4, the reduced scattering coefficients of α-SrO·3B_2O_3:Sm^{2+} at 453 nm, 555 nm, and 680 nm wavelengths grow with α-SrO·3B_2O_3:Sm^{2+} concentration. The deviations of the reduced scattering coefficients among three wavelengths are negligible. Correspondingly, the obtained results prove the stable scattering property of α-SrO·3B_2O_3:Sm^{2+} for different wavelengths.

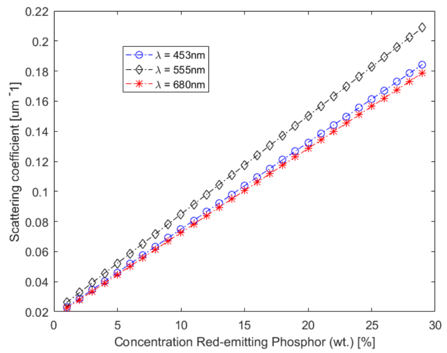


Fig. 2: Scattering coefficients of α-SrO·3B$_2$O$_3$:Sm^{2+} versus concentration red phosphor (%)

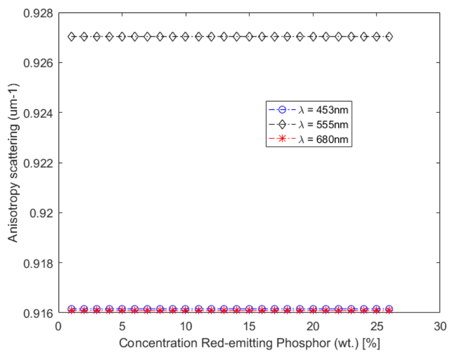


Fig. 3: Anisotropy scattering values of α-SrO·3B$_2$O$_3$:Sm^{2+} versus concentration red phosphor (%)

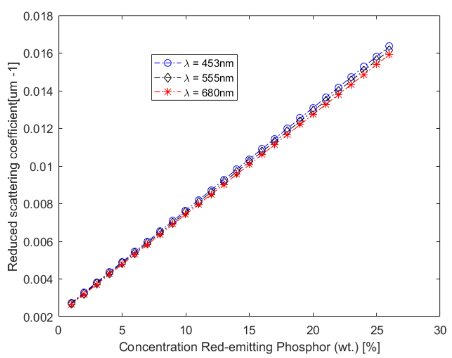


Fig. 4: Reduced scattering coefficients of α-SrO·3B$_2$O$_3$:Sm^{2+} versus concentration red phosphor (%)

As demonstrated in Figure 5 and Figure 6, both color rendering index (CRI) and color quality scale (CQS) grow with the α-SrO·3B$_2$O$_3$:Sm^{2+} concentration. This result can be obtained by the compensation of red-light in pc-LED when α-SrO·3B$_2$O$_3$:Sm^{2+} phosphor is employed. For 8500K CCT pc-LED with 30% α-SrO·3B$_2$O$_3$:Sm^{2+}, the highest CRI and CQS values that can be obtained are 80 and 70, respectively. This results show that this method can improve CRI and CQS in the high-CCT for the remote-packaging structure WLEDs. Furthermore, based on Figure 5 and Figure 6, both CRI and CQS values should be increased by adding more α-SrO·3B$_2$O$_3$:Sm^{2+} in to the phosphor layer. On another hand, by adding more α-SrO·3B$_2$O$_3$:Sm^{2+} can provide more disadvantage in luminous flux because of the excessive increase in the red-light spectrum region (Figure 7). As shown in Figure 7, the luminous flux has an increasing tendency from 2% to 14% and a decreasing tendency from more than 14% α-SrO·3B$_2$O$_3$:Sm^{2+}. The more concentration of the red-emitting α-SrO·3B$_2$O$_3$:Sm^{2+} phosphor the more scattering and reduce scattering processes in the phosphor layer of the WLEDs and it leads to more energy loss. It is the reason for decreasing the luminous efficacy when the concentration of the red-emitting α-SrO·3B$_2$O$_3$:Sm^{2+} phosphor more than 14%. For the 24% α-SrO·3B$_2$O$_3$:Sm^{2+} case, its luminous flux is approximately equal to the one of 2% α-SrO·3B$_2$O$_3$:Sm^{2+}. Moreover, the D-CCT are significantly decreased with the increase the red-emitting SrO·3B$_2$O$_3$:Sm^{2+} phosphor's concentration (Figure 8). As shown in Figure 8, the D-CCT are decreased from 13000K to 11000K, and from 6800K to 5200 K for the 8500K and 7000 K WLEDs, respectively. Finally, the involving of red-emitting α-SrO·3B$_2$O$_3$:Sm^{2+} conversion phosphor into the YAG:Ce phosphor compounding had a tremendous impact in increasing the optical performance of the 8500K and 7000K remote-packaging WLEDs.

III. CONCLUSIONS

In this paper, the red-emitting α-SrO·3B$_2$O$_3$:Sm^{2+} phosphor is presented to increase the optical performance of the 8500K and 7000K remote packaging WLEDs. From both simulation results and theoretical analysis, some conclusions are drawn as follows: a) The color uniformity (CRI and CQS) crucially increase while the concentration of

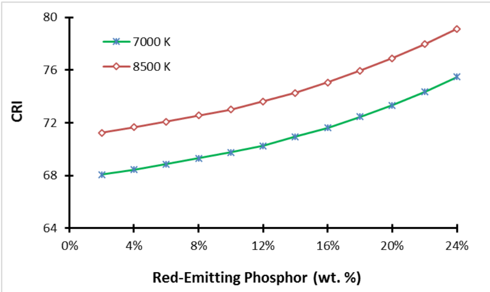


Fig. 5: Scattering coefficients of α-SrO·3B_2O_3:Sm^{2+} versus concentration red phosphor (%)

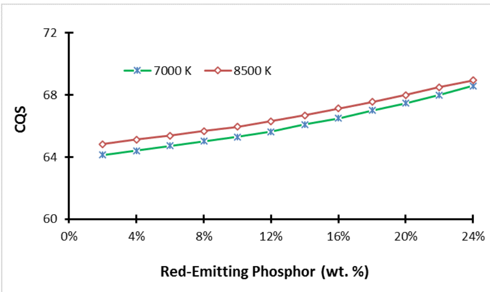


Fig. 6: CRI properties of WLEDs with various α-SrO·3B_2O_3:Sm^{2+} concentrations.

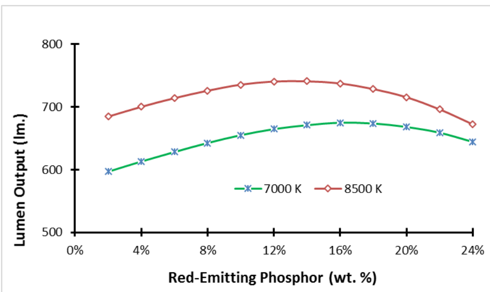


Fig. 7: Color quality scale (CQS) of WLEDs with various α-SrO·3B_2O_3:Sm^{2+} concentration.

α-SrO·3B_2O_3:Sm^{2+} phosphor varies from 2% to 24%. The highest values of CRI and CQS are 80 and 70, respectively, which occur in the 24% α-SrO·3B_2O_3:Sm^{2+} case.

b) The luminous flux increases with the concentration of α-SrO·3B_2O_3:Sm^{2+} until an optimal point, then decreases slightly beyond this point. In fact, the luminous flux at 2% and 24% α-SrO·3B_2O_3:Sm^{2+} are approximately equal to each other. This means that luminous flux can be kept while increasing CRI and CQS.

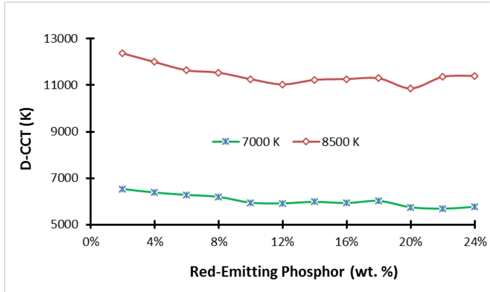


Fig. 8: D-CCT of WLEDs with various α-SrO·3B_2O_3:Sm^{2+} concentration.

c) The D-CCT of the WLEDs could be decreased crucially with the involvement of the red-emitting α-SrO·3B_2O_3:Sm^{2+} conversion phosphor. This study provides valuable technical information for RP-WLEDs manufacturing and material development of white LED applications. In further work, the influence of α-SrO·3B_2O_3:Sm^{2+} size on the lighting performance of remote packaging WLEDs should be investigated.

Acknowledgment

The authors appreciate the support of Dr. Phuong T. Tran Vice-Dean at Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam.

References

[1] *LED Packaging for Lighting Applications*, "Design of LED Packaging Applications," pp. 215–315, 2011.

[2] CHESIN, J., *Wide Band-gap Nanowires for Light Emitting Diodes*, 2015.

[3] WINKLER, H., Q. TRINH, P. BODROGI, Q. K. TRAN, *LED Lighting: Technology and Perception*, Weinheim: Wiley-VCH, 2015.

[4] LUO, X., R. HU, S. LIU, K. WANG, "Heat and Fluid Flow in High-Power LED Packaging and Applications," *Progress in Energy*

and Combustion Science, vol. 5, no.1, pp. 1–32, 2016.

[5] HU, R., X. LUO, S. LIU, "Effect of the Amount of Phosphor Silicone Gel on Optical Property of White Light-Emitting Diodes Packagin," *2011 12th International Conference on Electronic Packaging Technology and High Density Packaging*, 2011.

[6] TRAN, NGUYEN T., FRANK G. SHI., "Studies of Phosphor Concentration and Thickness for Phosphor-Based White Light-Emitting-Diodes," *Journal of Lightwave Technology*, vol. 26, no. 21, pp. 3556–3559, 2008.

[7] Shuai, Y., Y. HE, N. T. TRAN, F. G. SHI, "Angular CCT uniformity of phosphor-converted white LEDs: effects of phosphor materials and packaging structures," *IEEE Photonics Technology Letters*, vol. 23, no. 3, pp. 137–139, 2011.

[8] SOMMER, C., F.-P. WENZL, P. HARTMANN, P. PACHLER, M. SCHWEIGHART, S. TASCH, G. LEISING, "Tailoring of the Color Conversion Elements in Phosphor-Converted High-Power LEDs by Optical Simulations, *IEEE Photonics Technology Letters*, vol. 20, no. 9, pp. 739–741, 2008.

[9] LI, S., K. WANG, F. CHEN, S. ZHAO, Z. ZHAO, S. LIU, "Angular Color Uniformity Enhancement of Phosphor Converted White LEDs Integrated with Compact Modified Freeform TIR Components," *2012 13th International Conference on Electronic Packaging Technology & High Density Packaging,* 2012.

[10] LIU, Z., S. LIU, K. WANG, X. LUO, "Analysis of Factors Affecting Color Distribution of White LEDs," *2008 International Conference on Electronic Packaging Technology & High Density Packaging,* 2008.

[11] LIU, Z., S. LIU, K. WANG, X. LUO, "Optical Analysis of Color Distribution in White LEDs With Various Packaging Methods," *IEEE Photonics Technology Letters* 20 (24): 2027–2029, 2008.

[12] LIU, Z., S. LIU, K. WANG, X. LUO, "Effects of Phosphor's Location on LED Packaging Performance," *2008 International Conference on Electronic Packaging Technology & High Density Packaging*, 2008.

[13] MINH, T. H. Q., NGUYEN H. K. N., NGUYEN D. Q. A., H.-Y. LEE, "Red-Emitting α-SrO3B2O3:Sm2 Phosphor: an Innovative Application for Increasing Color Quality and Luminous Flux of Remote Phosphor White LEDs," *Journal of the Chinese Institute of Engineers*, vol. 40, no. 4, pp. 313–317, 2017.

[14] ANH, N. D. Q., H.-Y. LEE, T. T. PHUONG, N. H. K. NHAN, T. H. Q. MINH, T. H. LY, "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*, vol. 40, no. 3, pp. 228–234, 2017.

[15] TIN, P. T., N. H. NHAN, T. H. MINH, "Increasing the color quality of the 7000K conformal packaging MCW-LEDs by varied red-emitting K2SiF6:Mn4 conversion phosphor's size," *Cogent Engineering*, vol. 11, 2017.

[16] CHANDRAMOULI, K., S. H. CHO, Y. S. JUNG, K. S. SOHN, "Deep Red Color Emission in Sm2+ doped SrB4O7 Phosphor," In *Proceedings of the Asian Symposium on Information Display* New Delhi: The Electrochemical Society, 8-12 October 2006: 25-35, 2006.

[17] YEN, W. M., M. J. WEBER, *Inorganic Phosphors: Compositions, Preparation and Optical Properties,* Washington, D. C. CRC Press, 2004.

[18] *Optical Properties of Nanoparticle Systems.* "Beyond Mie's Theory II - The Generalized Mie Theory," pp. 317–339, 2011.

[19] FRISVAD, R. R., N. J. CHRISTENSEN, H. W. JENSEN, "Predicting the Appearance of Materials Using Lorenz–Mie Theory," *The Mie Theory Springer Series in Optical Sciences*, pp. 101–133, 2012.

[20] MACKOWSKI, D., "The Extension of Mie Theory to Multiple Spheres," *The Mie Theory Springer Series in Optical Sciences*, pp. 223–256, 2012.

[21] doi:10.1007/978-3-642-28738-1_2.

[22] LUO, X., R. HU, "Chip packaging: Encapsulation of nitride LEDs," *Nitride Semiconductor Light-Emitting Diodes* (LEDs), pp. 441-481, 2014.

[23] MISHCHENKO, M. I., L. D. TRAVIS, A. A. LACIS, *Scattering, Absorption, and Emission of Light by Small Particles*, Cambridge: Cambridge University Press, 2002.

[24] ZHONG, J., M. XIE, Z. OU, R. ZHANG, M. HUANG, F. ZHAO, "Mie Theory Simulation of the Effect on Light Extraction by 2-D Nanostructure Fabrication," *2011 Symposium on Photonics and Optoelectronics (SOPO)*, 2011.

[25] SOMMER, C., F. REIL, J. R. KRENN, P. HARTMANN, P. PACHLER, H. HOSCHOPF, F. P. WENZL, "The Impact of Light Scattering on the Radiant Flux of Phosphor-Converted High Power White Light-Emitting Diodes, " *Journal of Lightwave Technology*, vol. 29, no. 15, pp. 2285–2291, 2011.

[26] JONASZ, M., G. R. FOURNIER, "General Features of Scattering of Light by Particles in Water," *Light Scattering by Particles in Water*, pp. 87–143, 2007.

About Authors

Huu Khanh Nhan NGUYEN obtained his Ph.D. from the Institute of Research and Experiments for Electrical and Electronic Equipment, Moscow. He serves as Lecturer in Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research interests include VLSI, MEMS and LED driver chips.

Hoang Quang Minh TRAN (corresponding author) received his Ph.D. from Tomsk Polytechnic University, Tomsk City, Russian Federation. His research interests include high-voltage power systems, optoelectronics, wireless communications and network information theory. He serves as Lecturer in the Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam.

Hsiao-Yi LEE is Full Professor at National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan. He also is the Head of the Optoelectronics Research Group at Ton Duc Thang University, Ho Chi Minh City, Vietnam. His major interests are Optoelectronics and Applications.