TELKOMNIKA Telecommunication Computing Electronics and Control
Vol. 20, No. 6, December 2022, pp. 1343~1349
ISSN: 1693-6930, DOI: 10.12928/TELKOMNIKA.v20i6.24083

Superior hue output as well as lumen for WLEDs with dual-sheet distant layouts of phosphor

Phuc Dang Huu[1], Phan Xuan Le[2]
[1]Institute of Applied Technology, Thu Dau Mot University, Binh Duong Province, Vietnam
[2]Faculty of Mechanical - Electrical and Computer Engineering, School of Engineering and Technology, Van Lang University, Ho Chi Minh City, Vietnam

Article Info

Article history:

Received Jun 01, 2021
Revised Aug 24, 2022
Accepted Sep 03, 2022

Keywords:

Color uniformity
Luminous efficacy
Mg_2SiO_4:Mn^{2+}
Mie-scattering theory
WLEDs
Zn_2SiO_4:Mn^{2+},P

ABSTRACT

Remote phosphor constructions usually have color quality drawbacks but are more luminous in terms of lumen, surpassing conformal phosphor or in-cup layouts of phosphor. From this disadvantage, there is a great number of studies carried out to boost the chromatic performance in remote phosphor (RP) structures. This work focuses on using a two-layer RP or dual-film RP (DFRP) to improve the color rendering indices (CRI) as well as color quality scales (CQS) for white light emitting diodes (WLEDs). Two equivalent dual remote phosphor (DRP) structures for WLEDs operating at various temperatures of color including 5600 K, 7000 K, as well as 8500 K will be employed for our study. The study's idea involves putting one phosphor Zn_2SiO_4:Mn^{2+},P layer or one red phosphor Mg_2SiO_4:Mn^{2+} layer on top of the yellow YAG:Ce^{3+}. Subsequently modifying the concentration for each red and green phosphor to investigate the changes in color metrics and luminous flux. As a result, a suitable red and green phosphor concentration can be determined to acquire desired outcomes for each DFRP-WLED. Obtained results show that Mg_2SiO_4:Mn^{2+} performs significant boosting on both CRI and CQS, especially when being integrated with increasing concentration, thanks to the increased red-light presence for the WLED device. In addition, the sheet of phosphor Zn_2SiO_4:Mn^{2+},P benefits the luminous flux.

Corresponding Author:

Phan Xuan Le
Faculty of Mechanical - Electrical and Computer Engineering, School of Engineering and Technology
Van Lang University, Ho Chi Minh City, Vietnam
Email: le.px@vlu.edu.vn

1. INTRODUCTION

Semiconductor diodes, which utilize the light-conversion from the integrated phosphors to generate phosphor-converted white light-emitting diodes (pc-WLEDs), are considered a promising fourth-generation illuminating supply to be able to substitute the traditional one. This type of semiconductor diodes can be diversely employed in illumination [1]-[3]. Whereas the luminous intensity (LI) and correlated chromatic temperatures' uniformity (CCTU) in pc-WLEDs still demonstrate considerable limitation, though they have become increasingly common in various diverse domains of our everyday lives, such as billboarding, traffic lighting, and backlighting [4]-[6]. Further improvements in illuminating effectiveness and color standard are required according to the market's and applications' increasing needs [7]. The most typical method for producing illumination in white nowadays involves combining yellow illumination emitted by the yellow-emitting phosphor and the blue illumination generated by a light emitting diode (LED) chip. Despite the fact that this design seems to have good lighting brightness, the layout for the LED, as well as the placement for sheets of phosphor have a considerable effect in defining illuminating effectiveness, particularly the color rendering index (CRI) [8]-[10]. For the production of WLEDs, many popular processes for forming phosphorus surface coatings were suggested, including dispensing and conformal coatings [11], [12]. However, owing to the loss in luminous converting of phosphor material produced by a rise in heat generation at the LED and phosphor layer interface when the yellow phosphor layer was directly placed above the LED chip, resulting in greater temperature for the LED device as well as the phosphor sheet interface, these architectures do not give excellent color standard. As a result, lowering the heat output would increase phosphor efficiency while avoiding permanent phosphor degradation. Much prior research has shown that using a distant phosphor configuration, where the phosphor becomes distant from the thermal source (LED chip), the thermal influence can be reduced. LEDs may prevent backscatter and light circulation if the space separating the phosphor and the LED chip was big enough. Such a method is an ideal way of managing LED heat, as a result, to improve the illuminating efficacy and color intensity of LEDs [13]-[15]. Nevertheless, while the distant phosphor configuration is adequate for general illumination, it may not fulfill the needs of various other illuminating uses, which is likely why a new improvement for LEDs is required. Some new distant phosphor constructions are suggested for future improvement so that it is possible to lower phosphor reverse scattering aiming at the chip as well as to increase illuminating efficacy. Additional analysis revealed that an inverted cone lens encasement as well as a ring distant phosphor sheet around the LED chip may lead lighting generated by the chip of the LED to the LED exterior, lowering the degradation resulting from inner backscattering within the LED device [16], [17]. Greater angular-dependent CCTU and chromatic consistency are achievable with a patterned remote phosphor (RP) having a clear region without a daubing phosphorus film for the bordering area [18]. Furthermore, in comparison to a typical pattern, the patterned sapphire substrate utilized in the RP could give significantly greater far-field CCTU [19]. To increase the luminous intensity of LEDs, a distant phosphor with dual-film remote phosphor (DFRP) packaging is presented. The previous research aimed at enhancing the chromatic homogeneity and illuminating beam of WLEDs with a distant phosphor configuration. These experiments, however, are limited to single-chip WLED models with low color temperatures. Meanwhile, it's difficult to improve the optic parameter for WLEDs at significant color temperature. Moreover, there has been no study performed to compare the efficacy of various dual-layer phosphor designs. As a result, selecting a strategy to increase color standard or illuminating beam is extremely challenging for producers.

This paper discusses using two DFRP configurations for heightening the chromatic performance in WLEDs operating at various hue temperatures measured at 5600 K, 7000 K, as well as 8500 K. The first idea is to boost the green spectral energy inside a WLED by integrating green-phosphor $Zn_2SiO_4:Mn^{2+}$,P film, which will lead to greater luminescent intensity (LI). The second idea is to get the red-spectra enhancement by using a red phosphor film of $Mg_2SiO_4:Mn^{2+}$ in WLED packaging, which will lead to greater color rendering metrics including color rendering indices and color quality scales, abbreviated as CRI and color quality scales (CQS), respectively. Our research will thoroughly demonstrate the chemical composition of $Mg_2SiO_4:Mn^{2+}$ influencing the light attributes in WLEDs as well. The results show the improvements in both CRI and CQS with the presence of the $Mg_2SiO_4:Mn^{2+}$ sheet. However, when concentrations of $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$ are excessive, the degradation in lighting efficiency will be initiated. Thus, it is necessary to manipulate and keep their concentrations under suitable numbers, which eliminates such unwanted drawbacks. During this work, three differences when introducing a red or green sheet of phosphor above one $YAG:Ce^{3+}$ film are observed: one is an increased red or blue illumination composition that increases the emission spectrum for the white-illumination band, a key to increasing chromatic performance. Second, the optical dispersion and propagation inside WLEDs can be inversely proportional to the added phosphors' concentration. Therefore, suitable phosphor concentrations become important for keeping the WLEDs' lumen.

2. PREPARATION

2.1. Preparation of $Mg_2SiO_4:Mn^{2+}$ and $Zn_2SiO_4:Mn^{2+}$,P particles

The optic characteristics of phosphors are strongly influenced by their chemical composition. As a result, while applying to WLEDs, each of their components must be thoroughly examined. At peak wavelengths of 2.04 and 2.35 eV, $Zn_2SiO_4:Mn^{2+}$,P emits a green-orange light. The presence of the Mn^{2+} ion contributes to the higher luminous efficiency of $Zn_2SiO_4:Mn^{2+}$,P. Furthermore, $Mg_2SiO_4:Mn^{2+}$ emits red light and its peak wavelength is 1.88 eV. The presence of an emission peak indicates that the red phosphor material $Mg_2SiO_4:Mn^{2+}$ is more efficient, implying that the optic efficiency is greater [20], [21]. A spectral match with the blue light from the chip of LED must be required for these phosphors to be effective. These phosphors' absorption spectrum must match the blue chip's emission spectrum. $Mg_2SiO_4:Mn^{2+}$ has a very excellent absorption spectrum for absorbing light emitted in many bands. Because the yellow phosphor layer converts both blue and yellow light, not only blue light is generated. Likewise, the absorption spectrum of $Zn_2SiO_4:Mn^{2+}$,P ranges from 2.04 to 2.35 eV, with an absorption efficiency of greater than 70%.

Prior to doing an optic simulation of the particles $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$, the input factors, consisting of the concentration, granule measurement, excitation spectrum, absorption spectrum, as well as discharge spectrum of phosphor, must be experimentally investigated. Phosphor concentration and size are the unknown that must be discovered in order to get the best-LED color and illuminating beam quality [22]-[23]. The spectral properties do not change over time. The sizes of the phosphor particles are fixed on average at 14.5 µm, based on the outcomes of the earlier investigation. Meanwhile, the concentrations of the phosphors $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$ need to be calibrated for determining the optimal value. Hence, this work is carried out to fulfill this objective.

2.2. Designing packages of green-yellow DFRP and red-yellow DFRP

Two DFRP-WLED models integrating nine LED chips are utilized for this work, as indicated in Figure 1. Each of these blue chips has a power reaching 1.16 W as well as a peak wavelength reaching 453 nm. Figure 1(a) and Figure 1(b) show the physical LED configuration and its optic parameters in detail, respectively. The next stage is to create distant phosphor models to determine the appropriate amounts of $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$. Two green-yellow DFRP and red-yellow DFRP models, shortened as GYRP and RYRP, respectively, are offered in this research. A pair of phosphor sheets are positioned above the blue chips to make up the GYRP structure. We place the $YAG:Ce^{3+}$ sheet above the $Zn_2SiO_4:Mn^{2+}$,P sheet, which can be seen via Figure 1(c). Similarly, the phosphor films of $Mg_2SiO_4:Mn^{2+}$ and $YAG:Ce^{3+}$ comprising the RYRP configuration, demonstrated via Figure 1(d), are positioned on the LED chip cluster, in which the red $Mg_2SiO_4:Mn^{2+}$ is above yellow $YAG:Ce^{3+}$. Both GYRP and RYRP profiles are employed to boost the color standard and illuminating beam of WLEDs. The increase of the red and green light dispersion and combination in WLEDs is critical to obtain this. Moreover, $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$ concentrations must be changed substantially. Figure 2 shows the concentrations of blue phosphorus $Zn_2SiO_4:Mn^{2+}$,P, red phosphorus $Mg_2SiO_4:Mn^{2+}$, and yellow phosphorus $YAG:Ce^{3+}$ changing in the opposite direction. The first is that mean correlated color temperature (CCTs) will be maintained as a result of this adjustment. Secondly, the dispersion, along with the absorptivity for the pair of phosphor sheets in WLEDs would be altered by this change. This can considerably influence the WLEDs' color intensity and illuminating beam. The color intensity of WLEDs is thus determined by the concentrations of $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$ used. $YAG:Ce^{3+}$ concentrations were lowered to maintain CCTs average when $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$ concentrations rose from 2 wt% – 20 wt%. (Figure 2(a)) and 2 wt% – 26 wt%. (Figure 2(b)). The WLED devices under varying hue temperatures measured at 6600 K as well as 7700 K show the same phenomenon.

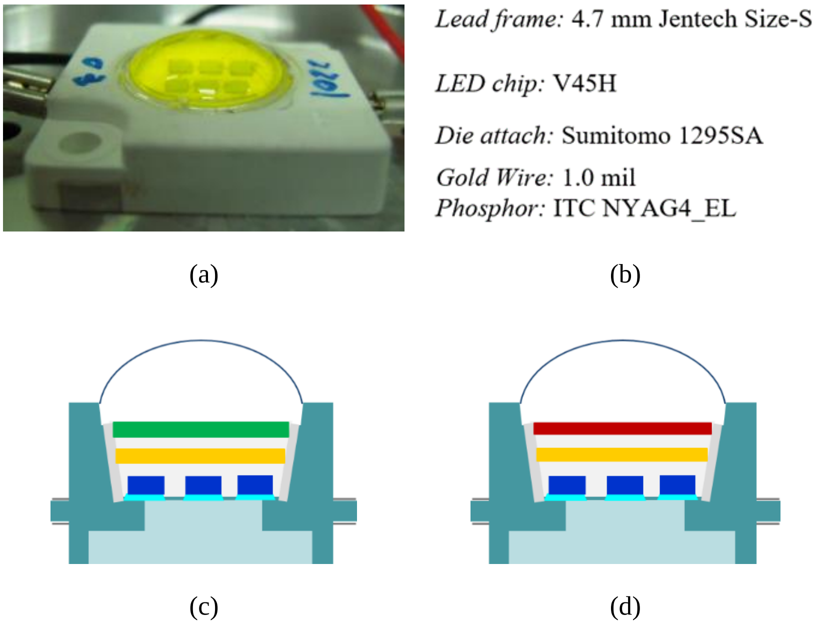


Figure 1. Illustrations of pc-WLEDs: (a) the actual MCW-LED, (b) its parameters, (c) DFRP using $Zn_2SiO_4:Mn^{2+}$,P, and (d) DFRP using $Mg_2SiO_4:Mn^{2+}$

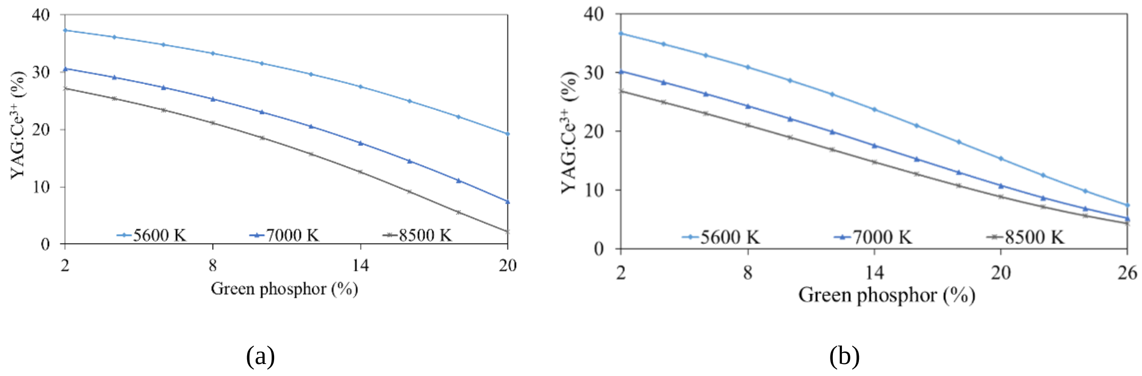


Figure 2. Concentrations of yellow-emitting phosphor YAG:Ce^{3+} in (a) green-yellow DFRP (GYRP) and (b) red-yellow DFRP (RYRP) for keeping the average CCTs

The influence of Mg_2SiO_4:Mn^{2+} concentrations on emission spectra of WLEDs is clearly depicted in Figure 3. A decision is made based on the specifications of the producers. WLEDs with high color intensity standards can lower illuminance by a tiny amount. The quantity of Zn_2SiO_4:Mn^{2+},P increased the intensity trend in the two light spectral ranges 420 nm – 480 nm as well as 500 nm – 640 nm. Such a rise of the discharge spectra of these two areas indicates a rise in the illuminance emitted. In addition, the scattering of emitted blue lights in WLEDs increases, i.e. scattering in both layers of phosphor and in WLEDs increases, resulting in favor of color uniformity. When using Zn_2SiO_4:Mn^{2+},P, this is an essential result. The trend in the spectral red element in the range between 648 and 738 nm surges alongside the Mg_2SiO_4:Mn^{2+} content, as can be seen. However, without a rise in the emission spectra for the remaining zones, 420 nm – 480 nm along with 500 nm – 640 nm, this is not significant. The 420 nm – 480 nm dual-band emission spectral rise aids in increasing blue-light scattering. A wider emission spectrum is represented by a greater color temperature. As a result, color standard and illuminating beam are improved. When using Mg_2SiO_4:Mn^{2+}, this is the most essential outcome. Notably, manipulating the WLEDs' chromatic performance at great temperatures can be particularly burdensome [24]. This study confirms that Mg_2SiO_4:Mn^{2+} can enhance the color standard of WLEDs even at 5600 K and 8500 K hue temperatures.

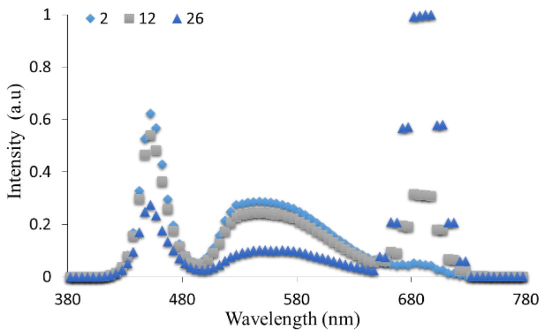


Figure 3. Emission spectra of WLEDs

3. COMPUTATION AND DISCUSSION

When light reaches an object, the CRI determines its true color. The color unbalance between red, blue, green, and yellow colors, the primary color shades essential to the white-light formation, is caused by an excessive rise of green light. This has an impact on the white-light chromaticity of pc-LEDs, resulting in lower color fidelity. The CRI decreases slightly as the Zn_2SiO_4:Mn^{2+},P concentration starts to increase, which can be seen in Figure 4(a). However, because CRI is merely a decent element of CQS, this is acceptable. It is harder to acquire the CQS index, which would be more essential than CRI. As the Zn_2SiO_4:Mn^{2+},P concentration is less than 8%, CQS does not change (Figure 4). Thus, Zn_2SiO_4:Mn^{2+},P when being integrated into the DFRP package should keep a concentration less than or equal to 8 wt%, so that the CQS consistency is possibly accomplished.

In all three typical CCTs of Figure 4(b), the CRI value rose with the phosphor concentration $Mg_2SiO_4:Mn^{2+}$, displayed via the absorptivity for the layer of red phosphor. These red phosphor particles absorb LED-emitted blue lights and convert them to red light. $Mg_2SiO_4:Mn^{2+}$ particles also absorb yellow light, but according to the material's absorption features, this red-emitting phosphor performs greater blue light absorption than the yellow absorption. And so, the WLEDs' red element is boosted with the addition of $Mg_2SiO_4:Mn^{2+}$, leading to greater CRI. In modern WLED selection parameters, CRI can be considered among the critical optical assessments. This probably results in the fact that superior CRI will make a WLED device more costly in the lighting market. Fortunately, using phosphor material such as $Mg_2SiO_4:Mn^{2+}$ to stimulate the CRI factor of the WLED has the benefit of cost-effectiveness, making it applicable in mass production.

As demonstrated, the high CRI cannot assure the high color quality for the white light, since it is just a component for assessing another color metric of WLEDs – CQS. Particularly, CRI is a part of CQS which also combines the aspects of viewer preference and the coordination of the chromatic gamut [25]-[27]. This indicates the wider coverage of CQS, making it almost a real universal color quality measure. The augmentation of CQS in the presence of the distant phosphor layer $Mg_2SiO_4:Mn^{2+}$ is shown in Figure 5(a). CQS increased considerably when $Mg_2SiO_4:Mn^{2+}$ concentrations were raised. Obviously, the use of $Mg_2SiO_4:Mn^{2+}$ could initiate the growth of color intensity of WLEDs with a DFRP configuration. This result can be the importance of using the red phosphor layer of $Mg_2SiO_4:Mn^{2+}$ to boost the DFRP-WLED's color intensity. Nonetheless, the drawback in LI that may happen when using high-concentration $Mg_2SiO_4:Mn^{2+}$ should be looked out. In contrast, the increase in green-phosphor $Zn_2SiO_4:Mn^{2+}$,P in the GYRP structure does not benefit the CQS of the WLED as it causes a drop in this parameter, as presented in Figure 5(b).

Generally, the WLED with great color performance could lower its luminous intensity by a small value and vice versa. Therefore, it is vital to demonstrate the luminous tendency of the two DFRPs to understand and figure out the best concentration for each phosphor in use. According to Figure 3, the GYRP is likely to be capable of enhancing the luminous flux since the blue emission intensity is higher than that of the RYRP one. The luminous fluxes of two DFRPs are demonstrated in Figure 6.

We can observe from Figure 6 that WLEDs with dual-layer distant phosphor have a higher luminous efficiency than those with single-layer phosphor. As a result, the effectiveness of the emitted light beam of these DFRPs has been shown in this article. Figure 6(a) indicates that with the increase of the $Zn_2SiO_4:Mn^{2+}$,P concentration (2 wt% – 20 wt%), the generated lighting beam increased dramatically. The concentration for the $Mg_2SiO_4:Mn^{2+}$ sheet will also substantially impact the lighting beam of the DFRP. Apparently, through employing the law of Lambert-Beer, the attenuation coefficient μ_{ext} increases accordingly to the $Mg_2SiO_4:Mn^{2+}$ content, while displaying an opposite behavior for the illumination progation power. As such, by adjusting the breadth for these phosphor films in WLEDs, the luminous flux declines as the $Mg_2SiO_4:Mn^{2+}$ content rises. We can clearly see in Figure 6(b) that the lumen is lowered at all three CCTs. As the $Mg_2SiO_4:Mn^{2+}$ concentration is at 26 wt%, the reduction of LI is outstanding. Considering the benefits of the layer of red $Mg_2SiO_4:Mn^{2+}$, such as greater CRI as well as CQS, in line with the superior lumen power to that of the SFRP (without red phosphor layer), the decreasing LI in the RYRP configuration can be accepted. The remaining issue is dependent on the manufacturer's objective of selecting the optimal $Mg_2SiO_4:Mn^{2+}$ concentration for mass manufacturing of these WLEDs.

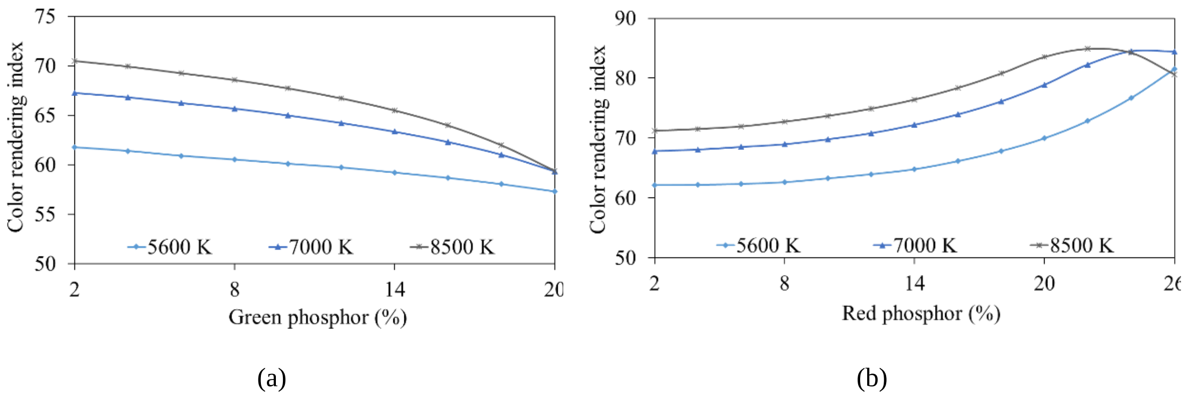
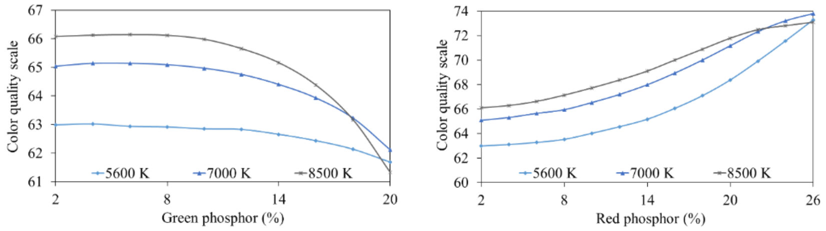
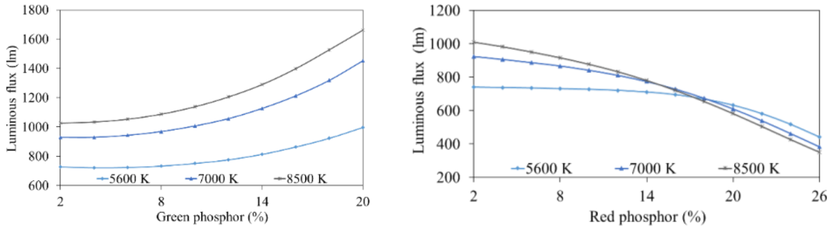


Figure 4. Color rendering indices of (a) GYRP and (b) RYRP as a function of modifying $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$ concentrations, respectively



(a) (b)

Figure 5. The color quality scale of (a) GYRP and (b) RYRP as a function of modifying $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$ concentrations, respectively



(a) (b)

Figure 6. The luminous flux of (a) GYRP and (b) RYRP as a function of modifying $Zn_2SiO_4:Mn^{2+}$,P and $Mg_2SiO_4:Mn^{2+}$ concentrations, respectively

4. CONCLUSION

The effects of the green phosphor $Zn_2SiO_4:Mn^{2+}$,P and the red phosphor $Mg_2SiO_4:Mn^{2+}$ on the CRI, CQS, and LI of two DFRP structures are discussed for the research. The research has shown that $Mg_2SiO_4:Mn^{2+}$ is a great option for improving color intensity, through employing the scattering theory of Mie theory as well as the law of Lambert-Beer. Besides, WLEDs use $Zn_2SiO_4:Mn^{2+}$,P as a luminous flux enhancement material. This applies not just to WLEDs at 5600 K, but also to WLEDs at 8500 K or higher. As a result, the findings yielded by our research could attain the objective of enhancing white light color intensity, which is hard to do using the distant-phosphor structure. The emitted luminous flux does, however, have a little disadvantage. The color intensity and luminous flux are greatly diminished as the $Zn_2SiO_4:Mn^{2+}$,P or $Mg_2SiO_4:Mn^{2+}$ concentration is significantly raised. As a result, depending on the manufacturer’s objectives, selecting an appropriate concentration becomes critical. Our research has provided useful data to create WLEDs with higher performance.

ACKNOWLEDGEMENTS

This study was financially supported by Van Lang University, Vietnam.

REFERENCES

[1] H. Daicho, K. Enomoto, H. Sawa, S. Matsuishi, and H. Hosono, "Improved color uniformity in white light-emitting diodes using newly developed phosphors," *Optics Express*, vol. 26, no. 19, pp. 24784-24791, 2018, doi: 10.1364/OE.26.024784.
[2] S. K. Abeysekera, V. Kalavally, M. Ooi, and Y. C. Kuang, "Impact of circadian tuning on the illuminance and color uniformity of a multichannel luminaire with spatially optimized LED placement," *Optics Express*, vol. 28, no. 1, pp. 130-145, 2020, doi: 10.1364/OE.381115.
[3] Y. -L. Piao *et al.*,"Improving the quality of full-color holographic three-dimensional displays using depth-related multiple wavefront recording planes with uniform active areas," *Applied Optics*, vol. 59, no. 17, pp. 5179-5188, 2020, doi: 10.1364/AO.387377.
[4] Q. Xu, L. Meng, and X. Wang, "Nanocrystal-filled polymer for improving angular color uniformity of phosphor-converted white LEDs," *Applied Optics*, vol, 58, no. 27, pp. 7649-7654, 2019, doi: 10.1364/AO.58.007649.
[5] W. J. Kim, *et al.*, "Improved angular color uniformity and hydrothermal reliability of phosphor-converted white light-emitting diodes by using phosphor sedimentation," *Optics Express*, vol. 26, no. 22, pp. 28634-28640, 2018, doi: 10.1364/OE.26.028634.
[6] C. Wu *et al.*, "Phosphor-converted laser-diode-based white lighting module with high luminous flux and color rendering index," *Optics Express*, vol. 28, no. 13, pp. 19085-19096, 2020, doi: 10.1364/OE.393310.
[7] A. K. Dubey, M. Gupta, V. Kumar, and D. S. Mehta, "Laser-line-driven phosphor-converted extended white light source with uniform illumination," *Applied Optics*, vol. 58, no. 9, pp. 2402-2407, 2019, doi: 10.1364/AO.58.002402.
[8] D. Lu *et al.*, "Synthesis and photoluminescence characteristics of the LiGd3(MoO4)5:Eu3+ red phosphor with high color purity

and brightness," *Optical Materials Express*, vol. 8, no. 2, pp. 259-269, 2018, doi: 10.1364/OME.8.000259.
[9] Y. Peng *et al.*, "Flexible fabrication of a patterned red phosphor layer on a YAG:Ce3+ phosphor-in-glass for high-power WLEDs," *Optical Materials Express*, vol. 8, no. 3, pp. 605-614, 2018, doi: 10.1364/OME.8.000605.
[10] X. Huang, S. Wang, B. Li, Q. Sun, and H. Guo, "High-brightness and high-color purity red-emitting Ca3Lu(AlO)3(BO3)4:Eu3+ phosphors with internal quantum efficiency close to unity for near-ultraviolet-based white-light-emitting diodes," *Optics Letters*, vol. 43, no. 6, pp. 1307-1310, 2018, doi: 10.1364/OL.43.001307.
[11] X. Huang, J. Liang, B. Li, L. Sun, and J. Lin, "High-efficiency and thermally stable far-red-emitting NaLaMgWO6:Mn4+ phosphorsfor indoor plant growth light-emitting diodes," *Optics Letters*, vol. 43, no. 14, pp. 3305-3308, 2018, doi: 10.1364/OL.43.003305.
[12] W. Wang and P. Zhu, "Red photoluminescent Eu3+-doped Y2O3 nanospheres for LED-phosphor applications: Synthesis and characterization," *Optics Express*, vol. 26, no. 26, pp. 34820-34829, 2018, doi: 10.1364/OE.26.034820.
[13] L. Li *et al.*, "Roller coaster"-like thermal evolution of the Er3+ ion's red photoluminescence in CaWO4:Yb3+/Er3+ phosphors," *Optics Letters*, vol. 44, no. 17, pp. 4411-4414, 2019, doi: 10.1364/OL.44.004411.
[14] C. Tian *et al.*, "Mn4+ activated Al2O3 red-emitting ceramic phosphor with excellent thermal conductivity," *Optics Express*, vol. 27, no. 22, pp. 32666-32678, 2019, doi: 10.1364/OE.27.032666.
[15] Q. Zhang, R. Zheng, J. Ding, and W. Wei, "Excellent luminous efficiency and high thermal stability of glass-in-LuAG ceramic for laser-diode-pumped green-emitting phosphor," *Optics Letters*, vol. 43, no. 15, pp. 3566-3569, 2018, doi: 10.1364/OL.43.003566.
[16] A. Ali *et al.*, "Blue-laser-diode–based high CRI lighting and high-speed visible light communication using narrowband green-/red-emitting composite phosphor film," *Applied Optics*, vol. 59, no. 17, pp. 5197-5204, 2020, doi: 10.1364/AO.392340.
[17] Y. Ye *et al.*, "Improving the color-rendering index of a tandem warm white organic light-emitting device by employing a simple fabrication process," *Optics Letters*, vol. 44, no. 4, pp. 931-934, 2019, doi: 10.1364/OL.44.000931.
[18] S. Bindai, K. Annapurna, and A. Tarafder, "Realization of phosphor-in-glass thin film on soda-lime silicate glass with low sintering temperature for high color rendering white LEDs," *Applied Optics*, vol. 58, no. 9, pp. 2372-2381, 2019, doi: 10.1364/AO.58.002372.
[19] R. Wan *et al.*, "Simultaneously improve the luminous efficiency and color-rendering index of GaN-based white-light-emitting diodes using metal localized surface plasmon resonance," *Optics Letters*, vol. 44, no. 17, pp. 4155-4158, 2019, doi: 10.1364/OL.44.004155.
[20] X. Yang, C. Chai, J. Chen, S. Zheng, and C. Chen, "Single 395 nm excitation warm WLED with a luminous efficiency of 104.86 lm/W and a color rendering index of 90.7," *Optical Materials Express*, vol. 9, no. 11, pp. 4273-4286, 2019, doi: 10.1364/OME.9.004273.
[21] R. Wan *et al.*, "Phosphor-free single chip GaN-based white light emitting diodes with a moderate color rendering index and significantly enhanced communications bandwidth," *Photonics Research*, vol. 8, no. 7, pp. 1110-1117, 2020, doi: 10.1364/PRJ.392046.
[22] H. -K. Shih, C. -N. Liu, W. -C. Cheng, and W. -H. Cheng, "High color rendering index of 94 in white LEDs employing novel CaAlSiN3: Eu2+ and Lu3Al5O12: Ce3+ co-doped phosphor-in-glass," *Optics Express*, vol. 28, no. 19, pp. 28218-28225, 2020, doi: 10.1364/OE.403410.
[23] Y. Ma *et al.*, "Broadband emission Gd3Sc2Al3O12:Ce3+ transparent ceramics with a high color rendering index for high-power white LEDs/LDs," *Optics Express*, vol. 29, no. 6, pp. 9474-9493, 2021, doi: 10.1364/OE.417464.
[24] N. D. Q. Anh, P. X. Le, and H. -Y. Lee, "Selection of a Remote Phosphor Configuration to Enhance the Color Quality of White LEDs," *Current Optics and Photonics*, vol. 3, no. 1, pp. 78-85, 2019, doi: 10.3807/COPP.2019.3.1.078.
[25] A. Ferrero, B. Bernad, J. Campos, N. Richard, C. F. -Maloigne, and M. Melgosa, "Goniochromatic assessment of gray scales for color change," *Journal of the Optical Society of America A*, vol. 37, no. 8, pp. 1266-1275, 2020, doi: 10.1364/JOSAA.394170.
[26] Z. Huang, Q. Liu, M. R. Pointer, W. Chen, Y. Liu, and Y. Wang, "Color quality evaluation of Chinese bronzeware in typical museum lighting," *Journal of the Optical Society of America A*, vol. 37, no. 4, pp. A170-A180, 2020, doi: 10.1364/JOSAA.381498.
[27] O. Kunieda and K. Matsushima, "High-quality full-parallax full-color three-dimensional image reconstructed by stacking large-scale computer-generated volume holograms, " *Applied Optics*, vol. 58, no. 34, pp. G104-G111, 2019, doi: 10.1364/AO.58.00G104.

BIOGRAPHIES OF AUTHORS

Phuc Dang Huu received a Physics Ph.D. degree from the University of Science, Ho Chi Minh City, in 2018. Currently, he is Research Institute of Applied Technology, Thu Dau Mot University, Binh Duong Province, Vietnam. His research interests include simulation LEDs material, renewable energy. He can be contacted at email: danghuuphuc@tdmu.edu.vn.

Phan Xuan Le received a Ph.D. in Mechanical and Electrical Engineering from Kunming University of Science and Technology, Kunming city, Yunnan province, China. Currently, He is a lecturer at the Faculty of Engineering, Van Lang University, Ho Chi Minh City, Viet Nam. His research interests are Optoelectronics (LED), Power transmission and Automation equipment. He can be contacted at email: le.px@vlu.edu.vn and phanxuanle.ts@gmail.com.