The effect green YF_3:ER^{3+},YB^{3+} phosphor on luminous flux and color quality of multi-chip white light-emitting diodes

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ABSTRACT

The purpose of this paper is to demonstrate the advantages of the green phosphor YF_3:Er^{3+},Yb^{3+} combined with multi-chip package to the enhancement of lighting efficiency of modern WLEDs. In an effort to improve the quality of white light-emitting diodes (WLEDs) and create a new generation of lighting device, green phosphor YF_3:Er^{3+},Yb^{3+} is added into the phosphor compounding of the WLED package to improve the color quality and lighting capacity. Through experiments, WLEDs with YF_3:Er^{3+},Yb^{3+} green phosphor has shown improved results in lighting performance specifically in color homogeneity and light output of WLEDs in the average correlated color temperatures (ACCT) range from 5600-7000 K. However, the color quality scale (CQS) declines gradually. Therefore, if the appropriate concentration and size of YF_3:Er^{3+},Yb^{3+} are determined, the performance of MCW-LEDs will be enhanced and become more stable.

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1. INTRODUCTION

Researchers have conducted intensive studies focusing on methods to increase the lighting performance of white light-emitting diode (WLED) packages without any disadvantage, and there are many positive results regarding the efforts in fulfilling this purpose. Specifically, many previous research papers mentioned that lumen output and color homogeneity are properties that need improvement [1]-[5]. After doing various experiments, Anh and his colleagues have finally found out that the combination of YAG:Ce^{3+} phosphor compounding with SiO_2 particles can be the solution to the concerning issue [6]. Moreover, with this mixture, the quality of multi-chip WLED packages can be enhanced considerably. Besides, mixing the yellow YAG:Ce^{3+} phosphor with the silicone glue is an important step, as the attained mixture can absorb the chromatic radiations from blue source and yellow source [7]-[13]. Specifically, emitted blue rays from the lighting LED chips would disintegrate in phosphorus compounds and then pass through phosphorus particles consecutively. In addition, the blue light will be metabolized by yellow YAG:Ce^{3+} phosphor particles during this process and simultaneously become weaker [14]-[16]. Nevertheless, the yellow light emitted tends to be stronger after each scattering event inside the LED packages. Therefore, the light output becomes more bluish when reaching the LED's surface, meanwhile, if the emitted light is not directly in front of LED chips, it will be more yellowish [17]-[19]. Thus, because of the differences in light intensity distribution, the yellow ring damaging the light quality of WLEDs is created.

However, if there is any solution that can perfect the materials used in WLEDs or impact the optical properties, better white light quality and lumen efficacy can be accomplished. Previously, Won and his partners worked together to prove that suitable phosphor geometry improves the amount of light extracted from WLEDs and results in a higher color quality scale (CQS). They combined the blue LED chips with various geometries of diffusor particles such as $(Ba,Sr)_2SiO_4:Eu^{2+}$ and $CaAlSiN_3:Eu^{2+}$ to get the optimal efficiency [20]. Meanwhile, the proposed work of Oh's group prioritized the development of lumen output and CRI by using triple-layer WLEDs configuration with each layer is a distinct color of green, yellow, or red [21]. Additionally, Zhang's team used multi-chromatic phosphor to accomplish the goal of bettering the CRI index of the LEDs [22]. Obviously, enhancing CRI and optical output are the targets of research, but color uniformity seems to be neglected. In addition, the scope of these researches solely covers WLEDs with one lighting chip, which is not practical considering how the multi-chip devices with high average correlated color temperatures (ACCTs) are often applied in current lighting applications.

This research uses the green $YF_3:Er^{3+},Yb^{3+}$ phosphor as supporting material for luminous flux and chromatic quality in the encapsulation layer of lighting configuration to achieve the highest index during the scattering process. Besides, the concentration of $YF_3:Er^{3+},Yb^{3+}$ phosphor is a factor that determines the lighting of WLEDs; thus if an appropriate concentration of this phosphor is selected, it will benefit the lighting performance and chromatic consistency of the device. The research process mentioned in this article includes 3 stages: i) Setting up the model of MCW-LEDs; ii) Integrating $YF_3:Er^{3+},Yb^{3+}$ and other materials into an encapsulation layer in the lighting configuration; iii) Computing the optical properties including the emitting wavelength range and the scattering intensity at different $YF_3:Er^{3+},Yb^{3+}$ concentrations. In short, if the mixture of $YF_3:Er^{3+},Yb^{3+}$ and $YAG:Ce^{3+}$ phosphors is applied to the LED's structure, the color homogeneity and lumen output can reach the highest values.

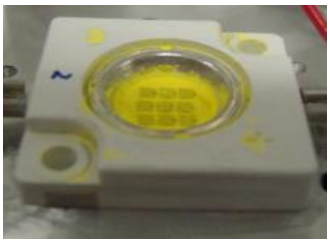
2. PREPARATION AND SIMULATION

2.1. Preparation of green $YF_3:Er^{3+},Yb^{3+}$ phosphor

Ingredients of $YF_3:Er^{3+},Yb^{3+}$ composition include YF_3, YbF_3, ErF_3, and ZnF_2 with the mole percentage of 78, 20, 2, and 10, respectively. To prepare a complete $YF_3:Er^{3+},Yb^{3+}$ compound for the research, a 3-main-stage process needs to be carried out in a strict order. Firstly, the chemical materials are mixed thoroughly in ethanol. Secondly, fire the compound in capped alumina crucible at temperature above 1100 ºC. However, there is a note that the firing process must be carried out in an inert or flourizing atmosphere. Thirdly, collect the products from the previous step, let it cool, and then wash them with water to remove flux. After that, we will get the final product having a green emission color and a 550 nm emission peak.

2.2. Construction of MC-WLEDs

The structure simulation of a real MCW-LED is built based on the application of the optical engineering software LightTools 8.1.0 and Monte Carlo. The simulating procedure consists of two main stages with flat silicone layer: first, constructing and fabricating the framework and the lighting characteristics of a WLEDs configuration; second, monitoring the impacts of $YF_3:Er^{3+},Yb^{3+}$ concentrations on the lighting efficiency and comparing with other WLEDs structures such as the conformal or in-cup structures at 5600 K and 7000 K CCT. Figure 1(a) demonstrates the details of conformal coating MCW-LEDs with the CCT of 5600 K and 7000 K. In addition to that description, a simulation of a MCW-LED without the $YF_3:Er^{3+},Yb^{3+}$ phosphor is also included. The size of reflector is 8 mm at base, 2.07 mm on the side, and 9.85 mm upper part. The conformal material layer covering the lighting chips has a pre-determined density of 0.08 mm. The chips are 1.14 mm^2 in size, 0.15 mm in height, and bounded to the gap in the reflector cup. Every lighting chip emits 1.16 W of energy at 453 nm. Figure 1(c) illustrates the dual-remote phosphor geometry in which the LED chips are coated with the two phosphor layers. Additionally, the Mie scattering is the main method to calculate the phosphor diffusion in this geometry. Besides, the phosphor particles used in this research has an average diameter of 14.5 μm, similar to the actual one. The phosphor compounding used for the simulation is comprised of the phosphor particles of $YF_3:Er^{3+},Yb^{3+}$, $YAG:Ce^{3+}$ that are well mixed with the silicone gel. The refractive indexes of these phosphor particles are 1.85, and 1.83, respectively, while that of the silicone glue is 1.52. After determining the refractive indices and sizes of material particles, it is possible to measure the emitting wavelength regions of that lighting device. The emission spectra of the phosphor compound are presented in Figure 2, these emission spectra will demonstrate the radiation emitted from the phosphor compound. In Figure 2, MCW-WLEDs with 10% $YF_3:Er^{3+},Yb^{3+}$ at 5700 K and 7000 K CCTs clearly have a light discharging improvement, which confirms that the participation of $YF_3:Er^{3+},Yb^{3+}$ particles in the phosphor compound benefits the luminous flux of LEDs configuration.



(a)

Lead frame: 4.7 mm Jentech Size-S

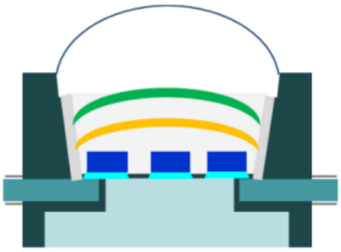
LED chip: V45H

Die attach: Sumitomo 1295SA

Gold Wire: 1.0 mil

Phosphor: ITC NYAG4_EL

(b)



(c)

Figure 1. Illustration of phosphor-converted MCW-LEDs as doping $YF_3:Er^{3+},Yb^{3+}$; (a) the actual MCW-LEDs and (b) its parameters; and (c) dual-remote phosphor geometry

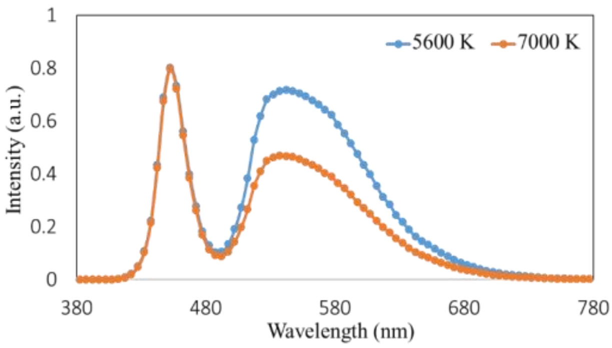


Figure 2. Emission spectra of MCW-LEDs

3. COMPUTATION AND DISCUSSION

To get the optical properties of phosphor compounding verified, the scattering coefficient μ_{sca} is calculated by applying the Mie-theory [23]-[25]. The (1)-(4) demonstrate the connection of the three different elements, including the scattering coefficient (SC), the wavelength, and the particle size of $YF_3:Er^{3+},Yb^{3+}$ phosphor.

$$\mu_{sca}(\lambda) = \frac{c}{\bar{m}} \bar{C}_{sca}(\lambda) \tag{1}$$

$$\bar{C}_{sca}(\lambda) = \frac{\int C_{sca,D}(\lambda) f(\mathrm{D}) \mathrm{dD}}{\int f(\mathrm{D}) \mathrm{dD}} \tag{2}$$

$$\bar{m} = \frac{\int m_i(\mathrm{D}) f(\mathrm{D}) \mathrm{dD}}{\int f(\mathrm{D}) \mathrm{dD}} \tag{3}$$

$$C_{sca}(\lambda) = \frac{P_{sca}(\lambda)}{I_{inc}(\lambda)} \quad (4)$$

In which, *f(D)* indicates the distribution of particles size, *c* stands for the amount of phosphor (g/cm^3), $C_{sca,D}$ is the scattering cross-section of the molecule with the length of D, $P_{sca}(\lambda)$ presents the scattered power by phosphor particles, and $I_{inc}(\lambda)$ is known as the irradiance intensity. In addition, $\bar{C}_{sca}(\lambda)$ is the scattering cross-section, and $\bar{m}$ is the phosphor particle mass being used in *f(D)*, respectively.

Figure 3 demonstrates the scattering coefficient (SC) of WLED if $YF_3:Er^{3+},Yb^{3+}$ phosphor is added to the configuration. The scattering coefficient evaluate the scattering capacity of the particles to create light. The $YF_3:Er^{3+},Yb^{3+}$ is probably the cause for considerable changes in SC of the phosphorus mixture. Furthermore, this verified that concentration and pre-stimulus of $YF_3:Er^{3+},Yb^{3+}$ can be used to tune color quality of CPG and IPG structures. Specifically, the SC tends to rise when the concentration of $YF_3:Er^{3+},Yb^{3+}$ at all particle measurements rises. If the particle size of the phosphor is approximately 1 μm, the SC gets the optimal value, without any consideration for its larger size. As a result, color uniformity is enhanced significantly. Meanwhile, when the particle size increases to approximately 7 μm, the SC becomes more stable regardless of the growth of $YF_3:Er^{3+},Yb^{3+}$ concentration, which will benefit the color quality scale (CQS) of the LEDs. Therefore, if the goal is the enhancement of CQS, the size of $YF_3:Er^{3+},Yb^{3+}$ phosphor particle can be approximately 1 μm or 7 μm. Besides, the SC connection with $YF_3:Er^{3+},Yb^{3+}$ concentration and particle size allows this material to effectively strengthen the lumen output and chromatic performance of lighting packages.

Fulfilling the specifications of a LED device is one of the most important goals to accomplish in this research paper. Additionally, the MCW-LED will have the best performance in the scope of the average CCTs. Hence, when the $YF_3:Er^{3+},Yb^{3+}$ phosphor concentration increases, the yellow phosphor $YAG:Ce^{3+}$ proportion must decrease to maintain color temperature at a constant value. The following expression demonstrates how the materials proportions add up in the encapsulation layer:

$$\sum W_{pl} = W_{yellowphosphor} + W_{silicone} + W_{yellow-greenphosphor} = 100\% \quad (5)$$

where, $W_{silicone}$, $W_{yellowphosphor}$ and $W_{yellow-greenphosphor}$ are proportions of weight in the phosphor layer of the silicone glue, the yellow $YAG:Ce^{3+}$ phosphor, and the green $YF_3:Er^{3+},Yb^{3+}$ phosphor, respectively.

In Figure 4, the chromatic variation fluctuates when there is $YF_3:Er^{3+},Yb^{3+}$ in the phosphor compounding. These deviation results demonstrate how much the expressed color from WLEDs fluctuate according to the added amount of $YF_3:Er^{3+},Yb^{3+}$ concentration. Obviously, the CCT peak-valley deviation shows a downward trend in accordance with the increase of $YF_3:Er^{3+},Yb^{3+}$ concentration, which means the spatial color distribution is benefited by $YF_3:Er^{3+},Yb^{3+}$ phosphor in the lighting configuration.

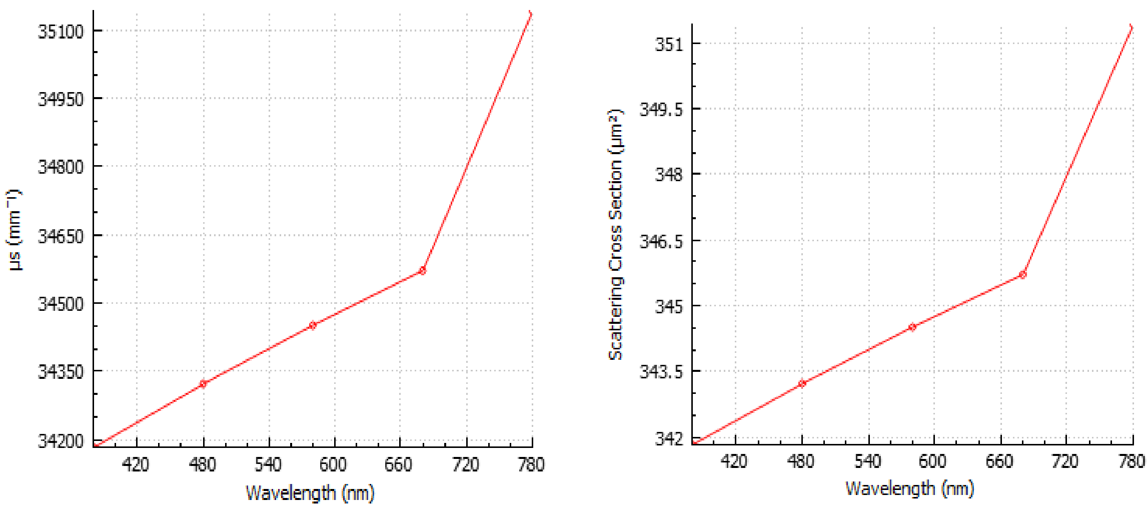


Figure 3. The computed values of scattering coefficients (right) and scattering cross-section (left) of phosphor compounding

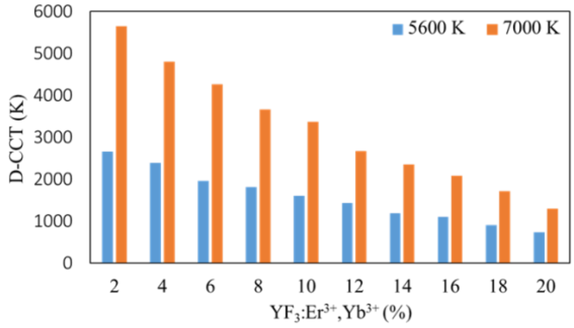


Figure 4. The CCT peak-valley deviation as a function of the concentration of YF_3:Er^{3+},Yb^{3+}

However, it is important to give optical properties of LEDs an equal focus because if we just concentrate on optimizing a factor, the other aspects of the optical systems will be weak. As a result, both CQS and lighting efficiency of WLED cannot reach highest values. Therefore, in case the priority is CRI, wide emission spectrum and the single color light obtained at 555 nm wavelength are the aspects for improvement. In our research, we consider the connection between CQS, lumen output, and CCT.

Figures 5 and 6 show the impacts of YF_3:Er^{3+},Yb^{3+} concentration on the WLEDs lighting enhancement, especially at high color temperature of 7000 K. The luminous efficacy in Figure 5 show how much radiation the WLED light source can provide in proportion to the power source, while the color quality scale in Figure 6 is a quality indicator that can access the rendering index, viewer preference and color coordinate of light source. As can be seen, the increasing amount of YF_3:Er^{3+},Yb^{3+} is followed by the rise in luminous efficiency. Meanwhile, the CQS tends to decline gradually if the concentration of YF_3:Er^{3+},Yb^{3+} exceeds a certain amount, specifically 8% wt. in our experiments. Thus, it can be concluded that if the YF_3:Er^{3+},Yb^{3+} concentration is set to a suitable amount, proposed amount from 8%-10% wt., it can support the process of bettering the color uniformity and the lumen output.

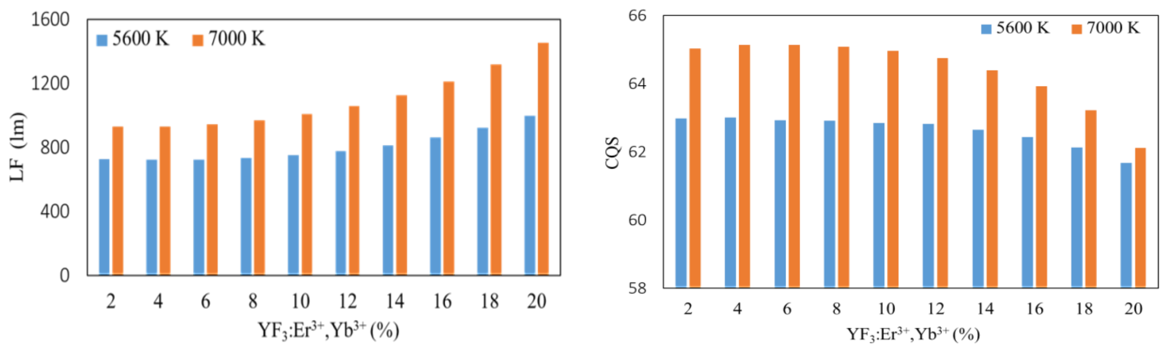


Figure 5. Luminous efficacy as a function of the concentration of YF_3:Er^{3+},Yb^{3+}

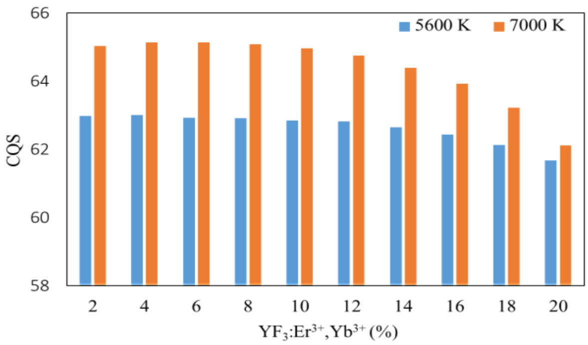


Figure 6. Color quality scale as a function of the concentration of YF_3:Er^{3+},Yb^{3+}

4. CONCLUSION

In conclusion, from the findings demonstrated in this research paper, the green $YF_3:Er^{3+},Yb^{3+}$ phosphor is useful for WLEDs enhancement regarding the chromatic quality and luminous flux. Specifically, after using the Mie-scattering theory to examine the scattering results, the color homogeneity shows different results as emitted light reflected back to the lighting configuration decreased regardless of the ACCT values. Moreover, the application of Monte Carlo simulation proves that the variation of lumen output is in connection with the $YF_3:Er^{3+},Yb^{3+}$ concentration. In other words, the luminous efficiency increases along with the change of $YF_3:Er^{3+},Yb^{3+}$ concentration. Thus, $YF_3:Er^{3+},Yb^{3+}$ phosphor is a suitable development phosphorus material to serve the WLEDs' production.

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