Using Green Emitting Phosphor for Improving Lighting Performance of In-cup Package White LED Lamps

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ABSTRACT

LED technology had a huge development in recent years with major benefits: long-life, high-efficiency, excellent performance, compactness. In this work, an innovative method for improving the performance of multi-chip white LED lamps (MCW-LEDs) by adding the green $Ce_{0.67}$ $Tb_{0.33}$ $MgAl_{11}$ O_{19}:Ce,Tb (CeTb) phosphor to their in-cup phosphor compounding is proposed, investigated and demonstrated. Firstly, CeTb was mixed to the in-cup phosphor package of MCW-LEDs. Then by varying CeTb concentration, lumen output and angular color uniformity (ACU) of MCW-LEDs was calculated and analyzed. The results showed that the lumen output and the ACU of 7000 K and 8500 K MCW-LEDs increased significantly in comparison with others related works. This method is a prospective ideal for future improving LED manufacture.

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1. INTRODUCTION

In the near studies, the quality enhancements of MCW-LEDs such as lumen output and ACU are considered [1]. Similarly, the quality of multi-chip white LED lamps are also enhanced significantly by adding SiO2 powder to YAG:Ce phosphor compound [2]. The yellow YAG:Ce phosphor material is mixed with silicone glue to form a phosphor compounding which absorbs the blue light of the blue chips and emits the yellow light. When the white light rays, which is achieved by the mixture of the colors, walk through phosphor particles. They are scattered in the phosphor compounding. The blue light is mixed with the yellow light during this process. Because of the absorption process of the yellow YAG:Ce phosphor particles, the blue light becomes weaker. Meanwhile, the converted yellow light is intensified through each scattering. Correspondingly, the difference of light intensity distributions can cause a yellow ring phenomenon [3]. To enhance light quality and lumen output, the multiple phosphors or the optical structures of white LED lamps could be optimized. Won et al. have demonstrated the strong influence of phosphor geometry on the lumen output of LED lamps with higher color rendering index (CRI) by adding green $(Ba,Sr)_2SiO_4:Eu^{2+}$ and red $CaAlSiN_3:Eu^{2+}$ phosphors with various phosphor structures to the blue LEDs [4]. Oh et al. have proposed G-A-R multi-package LED, which provides higher lumen output and good CRI [5]. Zheng et al. have enhanced the CRI of the LED lamp by using multi-chromatic phosphor [6]. The targets of these studies concentrate on improving CRI and lumen output without solving the ACU enhancement problems. Moreover, the studies only focus on single-chip white LED lamps, but it hardly really can improve the light quality of multi-chip white LED lamps having high CCTs. The green-emitting CeTb is a hexagonal poly-aluminate, which has a structure similar to magnetoplumbite, which is characterized by the hexagonal symmetry of the space group P63/mmc [7]. It's related compositions include CeO_2, Tb_4O_7, MgO, Al_2O_3, Ce^{3+} and Tb^{3+} ions, all of which were thoroughly mixed in agate mortar [8]. The Ce^{3+} ion plays a role of the sensitizer for Tb^{3+} luminescence in the green-emitting CeTb. CeTb is applied particularly for very high-loading and long lifetime fluorescent lamps. Correspondingly, it is one of the commercialized popular oxide phosphors.

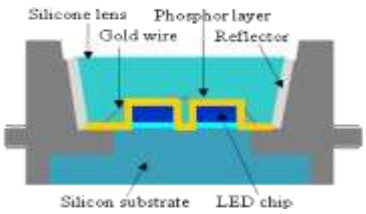
In this paper, a novel application of green CeTb phosphor particles in the phosphor compounding of MCW-LEDs to improve their color uniformity and lumen output is proposed, investigated and demonstrated. We show that the participation of the CeTb particles can enhance the scattering event of the phosphor compounding. Therefore, the light distribution of MCW-LEDs can be independent of their wavelengths. The uniform spatial color distribution of the LED can thus be accomplished. The research consists of 3 stages: 1) Simulation of MCW-LEDs;2) Putting CeTb into the phosphor compounding of the MCW-LEDs; 3) Analyzing the effects of CeTb concentration on the performance, including the enhancement of emission spectra and scattering event. The investigated results show that the ACU and lumen output can be increased significantly after mixing green CeTb and yellow YAG:Ce phosphors on comparison with other related works.

2. MAIN PART

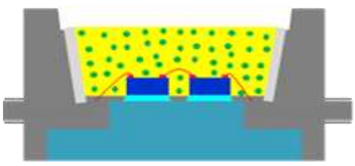
2.1. MCW-LEDs physical model

The phosphor layer mechanism of real MCW-LEDs with flat silicone coating is simulated by using LightTools 8.1.0 program. The main modeling work includes 1) Constructing the mechanical structures and the optical properties of MCW-LED lamps; 2) Verifying the optical changes of phosphor compounding through various CeTb concentration. The MCW-LED lamp with in-cup phosphor compounding having average CCTs of 7000 K and 8500 K is presented in Figure 1 (a). To compare the impacts of YAG:Ce and CeTb phosphors compounding on the performance of MCW-LED lamps, the in-cup phosphor structure having average CCTs of 700 K and 8500 K is also applied. Figure 1(b) shows the elements of the simulated MCW-LEDs without CeTb. The reflector has a bottom length of 8 mm, a height of 2.07 mm and a length of 9.85 mm at its top surface. The conformal phosphor compounding, with the fixed thickness of 0.08 mm, covers the nine chips. Each LED chip with the square base of 1.14 mm2 and the height of 0.15 mm is bonded in the cavity of the reflector. The radiant flux of each blue chip is 1.16 W, and the peak wavelength is 453 nm. As for the in-cup phosphor structure, the novel phosphor compounding is mixed in the silicone lens, as displayed in Figure 1 (c). The scattering of phosphor particles will be analyzed by using Mie-theory [8],[9]. In the research, the average diameters of the phosphor particles are set to be 14.5, which are the same as the actual parameters. The novel phosphor compounding is a mixture of CeTb and YAG:Ce particles and the silicone glue. The refractive indexes of CeTb and YAG:Ce phosphors and its silicone glues are in turn 1.85, 1.83 and 1.52, which are also the same as the actual parameters. Besides the refractive index and the size of the phosphor particles, we determine the emission spectra of the novel phosphor compound. The emission spectra of the in-cup phosphor compounding are verified by enhancing CeTb concentration to 1.0%, as resented in Figure 2. The results demonstrate that the lumen output of MCW-LEDs may be enhanced after mixing CeTb particles to phosphor compounds.

a



b



c

Figure 1. (a) The actual MCW-LED with in-cup phosphor layer, (b) Its schematic cross-sectional view, (c) The simulated in-cup phosphor packaging (CPP)

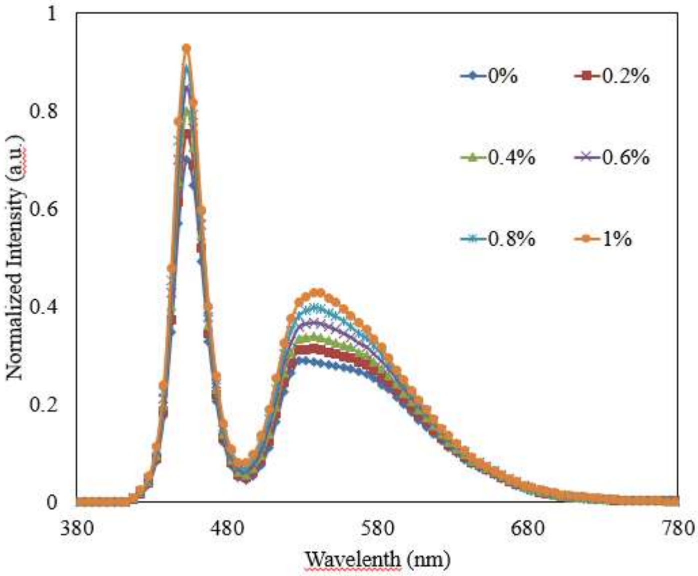


Figure 2. Emission spectra of multiple phosphors

This section is to verify the light scattering effect incurred by CeTb and phosphor particles in the proposed MCW-LED structure. Based on Mie-scattering theory [8],[10],[11], the scattering intensity functions and were computed by using MATLAB. Mie-scattering intensities and are plotted as functions of cos θ. The results are displayed on the polar coordinate system within the upper half circle (0<θ<π) and in the lower half circle (π<θ<2π). The angular scattering amplitudes, i_1 and i_2 can be expressed as:

$$i_1 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[a_n(x,m)\pi_n(\cos\theta) + b_n(x,m)\tau_n(\cos\theta) \right] \quad (1)$$

$$i_2 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[a_n(x,m)\tau_n(\cos\theta) + b_n(x,m)\pi_n(\cos\theta) \right] \quad (2)$$

Here, m is the refractive index of powder, x is the size parameter, and are the angular dependent functions, and are the expansion coefficients. The scattering intensities are calculated for 555 nm and 453 nm wavelengths, which are the emission peaks of the yellow YAG:Ce phosphor and the blue chips, respectively. Figure 3 displays the scattered light intensity distributions of CeTb and YAG:Ce particles on the upper half circle (0<θ<π/2). The scattering enhancement of phosphor compounding can be achieved after adding CeTb phosphor. Correspondingly, the angular color distribution of MCW-LEDs may also be reconfigured and improved with CeTb particles.

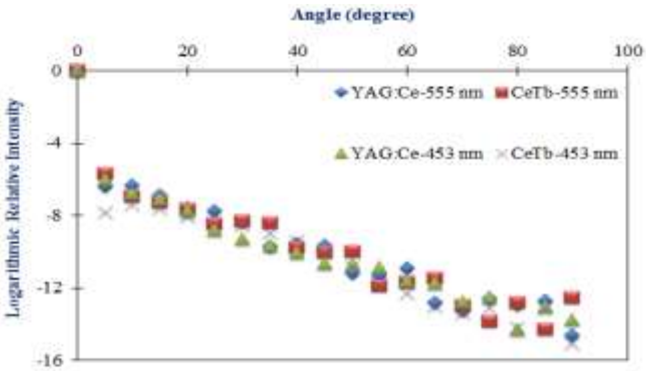


Figure 3. The light scattering distribution of CeTb and YAG:Ce particles in the phosphor layer of MCW-LEDs for 453 nm and 555 nm

2.2. Results and discussions

In this research, it is necessary to keep the MCW-LED work at CCTs of 7000 K and 8500 K for meeting the LED product specification. If the concentration of the green CeTb phosphor grows, its yellow YAG:Ce phosphor needs to be reduced for maintaining the mean CCTs of 7000 K and 8500 K. The weight percentage of the LED phosphor layer can be expressed as:

$$\sum W_{pl} = W_{yellow\ phosphor} + W_{silicone} + W_{green\ phosphor} = 100\% \qquad (3)$$

Here the $W_{silicone}$, $W_{yellow\ phosphor}$ and $W_{green\ phosphor}$ are in turn the weight percentage of the silicone glue, the yellow YAG: Ce phosphor and the green CeTb phosphor. The achieved simulation results of the angular color deviation of MCW-LED with and without CeTb in the phosphor compounding are shown in Figure 4. It can be observed that the CCT peak-valley deviation reduces significantly after involving CeTb. It means that the spatial color distribution of MCW-LEDs with CeTb is much flatter than that in the non-CeTb case. Also, the growing of the weight of CeTb increases continuously 0% to 1.0% for the phosphor in-cup packaging. The optimization of factors is based on one scalar objective function. If one single quantity is optimized, the optical system may perform very poorly in other aspects. For example, for the best CRI values, efficacy is very low. The reason is that good CRI requires broad source spectra, whereas efficacy is highest for monochromatic radiation with a wavelength of 555 nm [12]-[14]. In this study, CRI, luminous flux, and CCT P-V deviation values are three competing properties. Referring to the accomplished simulation results in Figure 5 and Figure 6, it can be found that the lumen output grows with growing concentration of CeTb. However, the results also show that the more CeTb concentration involved, the higher luminous flux, but less CRI we get. In summary, the MCW-LED packages with better-correlated color temperature (CCT) uniformity and higher luminous flux could be accomplished with the insignificant decrease of CRI.

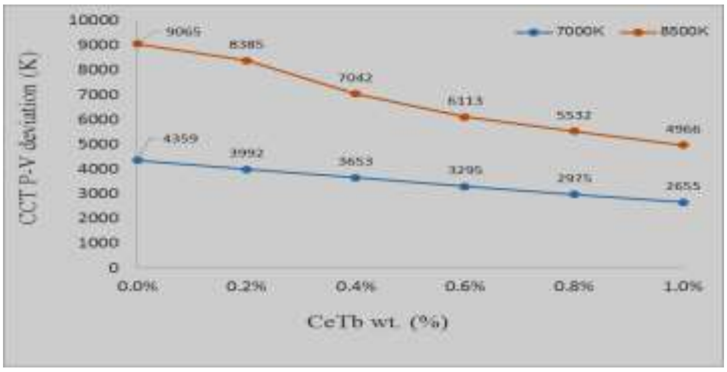


Figure 4. The angular CCT peak-valley (P-V) deviation with various CeTb concentration

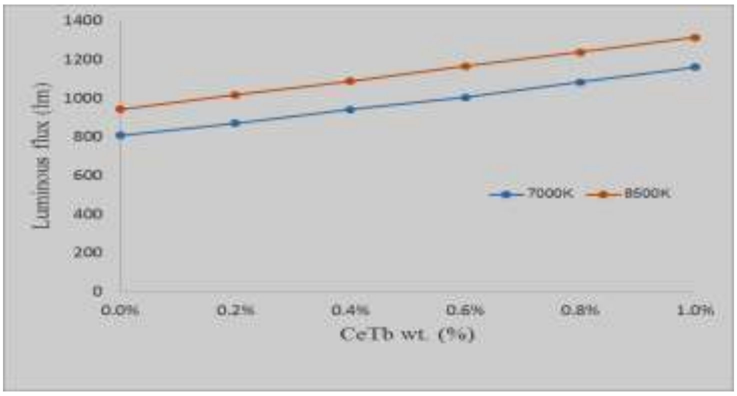


Figure 5. The lumen output at average CCTs 7000K and 8500 K with different CeTb concentration

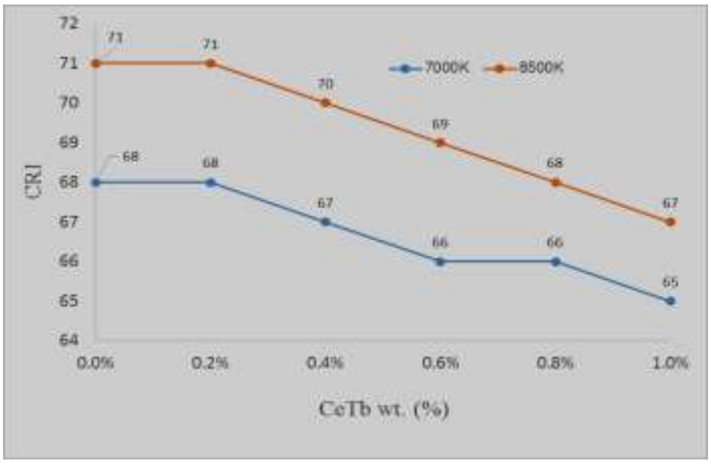


Figure 6. The color rendering index at average CCTs 7000K and 8500 K with different CeTb concentration

3. CONCLUSION

In the work, the green CeTb phosphor is proposed to use for improving the spatial color uniformity and the lumen output of MCW-LED lamps. Using the CeTb particles in phosphor compounding, the angular light distribution of the lamps can be adjusted by enhancing the scattering event, resulting in growing of the ACU. Moreover, the emission spectra of multiple phosphors grow with the CeTb concentration, so that the lumen output of MCW-LEDs increases significantly in comparison with other related works. Adding green CeTb phosphor to phosphor compounding of MCW-LED lamps is an innovative and prospective solution for LED technology in the near future. Also, more research in the effect of green CeTb phosphor size to the lighting performance of MCW-LED lamps is required to gap.

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