

# ENHANCING LIGHTING PERFORMANCE OF WHITE LED LAMPS BY GREEN EMITTING Ce,Tb PHOSPHOR

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**Abstract.** *With the development of high-efficiency and high-power Light-Emitting Diodes (LEDs), it has become possible to use LEDs in lighting and illumination. In last decades, developing a new method for improving lumen output and Angular Color Uniformity (ACU) is the main direction in LED technology. In this paper, an innovative approach for enhancing lighting performance (lumen output and angular color uniformity) of Multi-Chip White LED lamps (MCW-LEDs) was proposed and demonstrated by mixing the green  $Ce_{0.67}Tb_{0.33}MgAl_{11}O_{19}$ : Ce,Tb (CeTb) phosphor into their phosphor compounding. With varying CeTb concentration, ACU and lumen output with Conformal Phosphor Package (CPP) and In-cup Phosphor Package (IPP) are calculated, displayed and analyzed. The results show that the lumen output and the ACU of 7000 K and 8500 K MCW-LEDs increased remarkably in comparison with the older works. Using green CeTb is a prospective method for improving lighting performance of MCW-LEDs in future.*

## Keywords

*Angular color uniformity,  $Ce_{0.67}Tb_{0.33}MgAl_{11}O_{19}$ : CeTb, lighting performance, lumen output, multi-chip white LED lamps.*

## 1. Introduction

Multi-chip white LED lamps have many benefits for LED lighting applications such as long life, compactness, high efficiency, low power consumption [1]. The main lighting properties of MCW-LEDs are lumen output and the Angular Color Uniformity (ACU), which are considered and analyzed in many studies [2] and [3]. The yellow YAG: Ce phosphor material is mixed

with silicone glue to form a phosphor compounding which absorbs the blue light of the LED chips to emit the yellow light. The white light with various average Correlated Color Temperatures (CCTs) is achieved by the mixture of the yellow, blue and red light. Light rays go through phosphor particles and scatter in the phosphor compounding. The blue light is compounded with the yellow light during the operation of scattering. The blue light becomes weaker due to the absorption process of the yellow YAG: Ce phosphor particles. Meanwhile, the converted yellow light is amplified through each scattering. Correspondingly, the difference of light intensity distributions can cause a yellow ring phenomenon [4].

In purpose to enhance light quality and lumen output, the multiple phosphors or the optical structures of white LED lamps must be optimized. The substantial 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 was proposed in [5]. In another way, [6] and [7] provided G-A-R multi-package LED with higher lumen output and good CRI. The CRI of the LED lamps was enhanced by using multi-chromatic phosphor. In general, the above works only focused on improvement of CRI and lumen output without solving ACU enhancement problem. Moreover, these works only focused on single-chip white LED lamps, to this date very few works focused on improvement of the light quality of multi-chip white LED lamps with high CCTs.

The green-emitting CeTb is one type of hexagonal poly-aluminate. Moreover, its structure is similar to magnetoplumbite, which is characterized by the hexagonal symmetry of the space group  $P63/mmc$  [5]. Its 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 [7]. 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 popular commercialized oxide phosphors.

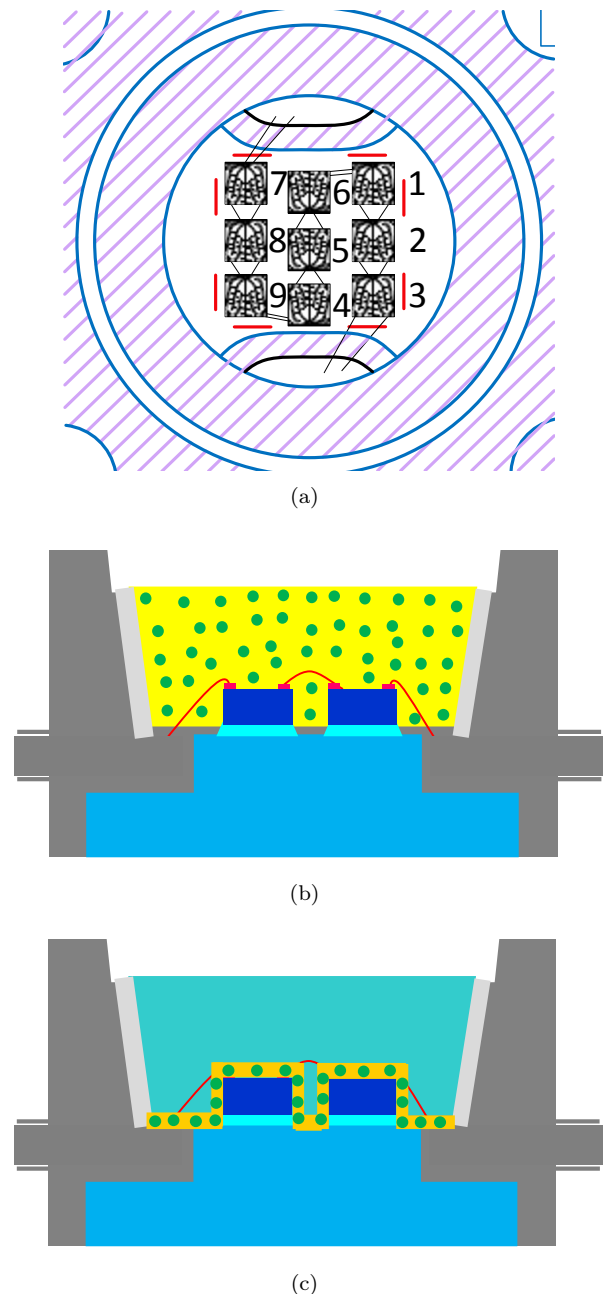
In this paper, an innovative application of adding green CeTb phosphor particles into the phosphor compounding of MCW-LEDs with Conformal Phosphor Package (CPP) and In-cup Phosphor Package (IPP) for improving color uniformity and lumen output is presented and demonstrated. Simulation results indicated that the participation of the CeTb particles enhanced the scattering event of the phosphor compounding. Therefore, the light distribution of MCW-LEDs could not depend on their wavelengths. After that, the uniform spatial color distribution of the MCW-LEDs could thus be accomplished. This research work has three parts. Firstly, the physical model of MCW-LEDs using the Light Tool simulation program was simulated. Then, by putting CeTb particles into the phosphor compounding of the MCW-LEDs with the conformal and in-cup package was proposed. Finally, the influence of CeTb particles concentration on the lighting performance of the MCW-LEDs was calculated, analyzed and demonstrated. The researched results showed that the ACU and lumen output of the MCW-LEDs increased significantly after mixing green CeTb with yellow YAG:Ce phosphor particles.

## 2. Physical and Mathematical Model of Real MCW-LEDs

By using LightTools 8.1.0 software, the physical model of the MCW-LEDs is presented and simulated. The modeling work can be divided into 2 main parts:

- Constructing the mechanical structures and the optical properties of MCW-LED lamps.
- Verifying the optical properties of phosphor compounding through varying CeTb particles concentration.

The 2-D model of MCW-LED lamps by using LightTools 8.1.0 software is presented in Fig. 1. In this model, 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 0.08 mm, which covers the nine chips. Each LED chip with a square base of 1.14 mm and a height of 0.15 mm is bonded in the cavity of the reflector shown in Fig. 1(a). The radiant flux of each blue chip is 1.16 W. For the conformal structure as shown in Fig. 1(b), the novel phosphor compounding is coated conformally on the chips. As for the in-cup



**Fig. 1:** (a) is the position diagram of chips, (b) and (c) are the simulated conformal and in-cup phosphor package.

phosphor structure, the novel phosphor compounding is mixed in the silicone lens, as displayed in Fig. 1(c). The scattering of phosphor particles could be analyzed by using Mie-theory. In this research, the average diameters of the phosphor particles are 14.5 nm, which are same as the real parameters [4]. The new phosphor compounding is the mixture of the CeTb and YAG:Ce particles, and the silicone glue. The refractive indexes of CeTb and YAG:Ce phosphors and its silicone glue are in turn 1.85, 1.83 and 1.52, which are same as the real parameters. Besides the refractive index and the size of the phosphor particles, the emission spectra of

the novel phosphor compounds was determined. The emission spectra of the conformal phosphor compounding are verified by enhancing CeTb concentration from 0 % to 20 %, as presented in Fig. 2(a). As for Fig. 2(b), the emission spectra of the in-cup phosphor compounding are displayed by varying CeTb concentration from 0 % to 1.0 %. The results demonstrated that the luminous efficiency of MCW-LEDs remarkably enhanced after compounding CeTb particles to phosphor compounds.

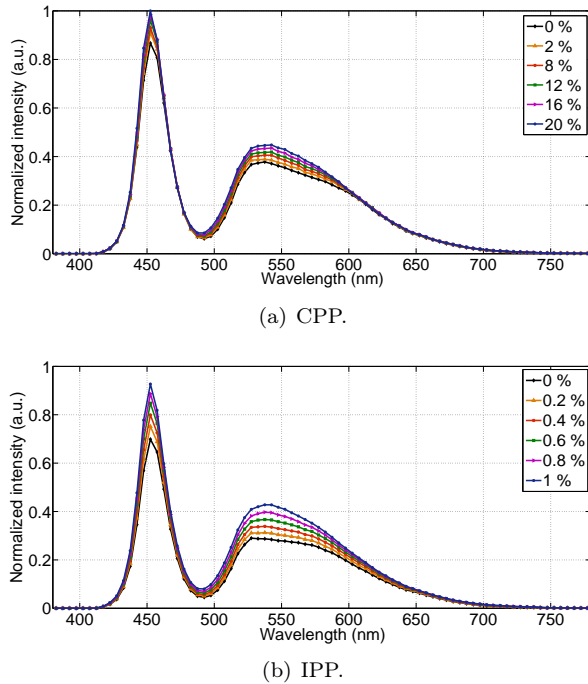


Fig. 2: Emission spectra of multiple phosphors.

In this section, Mie theory is applied to calculate the scattering of phosphor particles in an angle range from 0° to 360°. The angular light scattering intensities could be calculated by the below equations:

$$i_1 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \begin{bmatrix} a_n(x, m) \pi_n(\cos \theta) \\ b_n(x, m) \tau_n(\cos \theta) \end{bmatrix}, \quad (1)$$

$$i_2 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \begin{bmatrix} a_n(x, m) \tau_n(\cos \theta) \\ b_n(x, m) \pi_n(\cos \theta) \end{bmatrix}, \quad (2)$$

where  $m$  is a refractive index,  $x$  is a size parameter,  $\pi_n(\cos \theta)$  and  $\tau_n(\cos \theta)$  are the angular functions,  $a_n$  and  $b_n$  are the expansion coefficients. The scattering intensities are calculated for 555 nm and 453 nm wavelengths, which are the emission peaks of the yellow light of YAG:Ce phosphor and the blue light of chips, respectively.

Figure 3 displayed the scattered light intensity distributions of CeTb and YAG:Ce particles with wavelength (Fig. 3(a)) 453 nm, (Fig. 3(b)) 555 nm. 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 get better values with CeTb particles (Fig. 4).

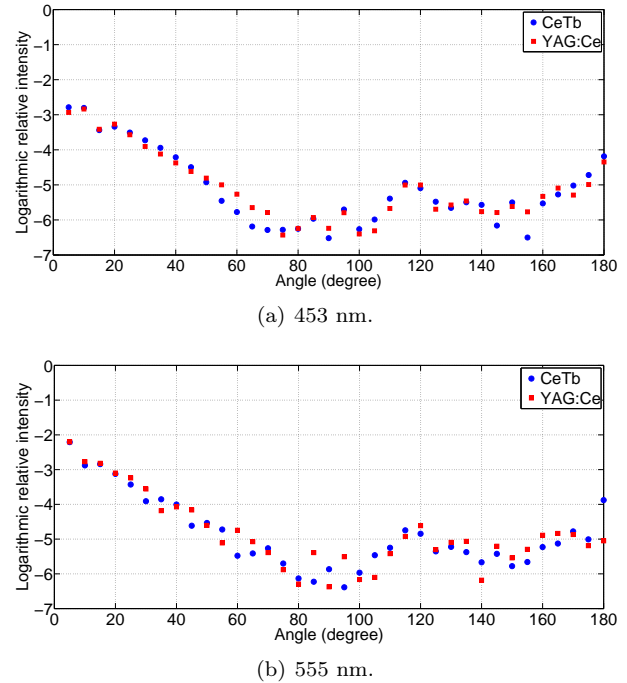


Fig. 3: Emission spectra of multiple phosphors.

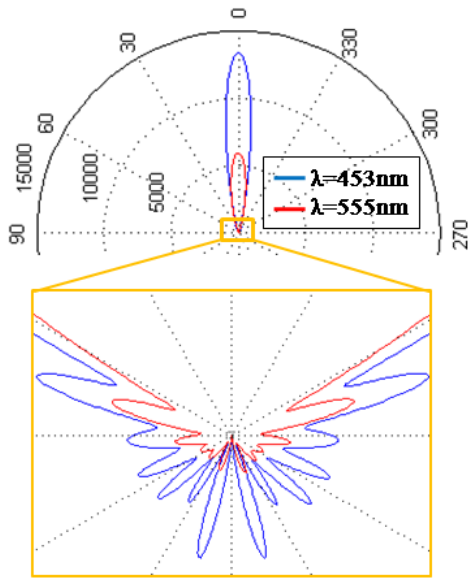
### 3. Simulation Results and Discussions

In this research, it is necessary to keep the MCW-LED work at high CCTs of 7000 K and 8500 K for meeting the LEDs product specification. If the green CeTb phosphor concentration grows, its yellow YAG:Ce phosphor concentration needs to be decreased in order to fix the CCTs of 7000 K and 8500 K. The weight percentage of the LED phosphor layer could be calculated as:

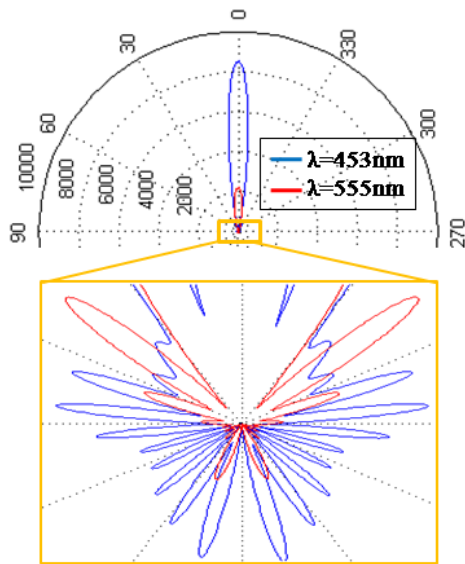
$$\sum W_{\text{phosphor layer}} = W_{\text{yellow phosphor}} + W_{\text{silicone}} + W_{\text{green phosphor}} = 100 (\%), \quad (3)$$

where the  $W_{\text{phosphor layer}}$ ,  $W_{\text{yellow phosphor}}$  and  $W_{\text{green phosphor}}$  are the weight percentage of the silicone glue, the yellow YAG:Ce phosphor and the green CeTb phosphor, respectively.

Figure 5 presented the angular color deviation of MCW-LEDs with CeT band without CeTb in the phosphor compounding for CPP (Fig. 5(a)) and IPP (Fig. 5(b)). From the simulation results, the CCT



(a) CPP.

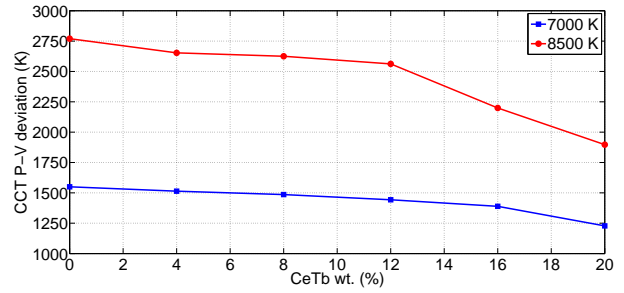


(b) IPP.

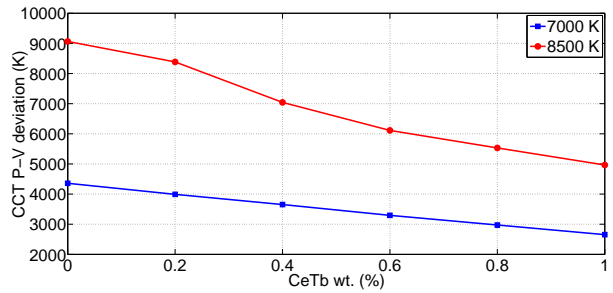
**Fig. 4:** The angular scattering amplitudes of the diffusional particles.

peak-valley Deviation (DCCT) reduces significantly after involving CeTb. It means that the spatial color distribution of MCW-LEDs with CeTb is much flatter than the non-CeTb case. In addition to that, the growing of the weight of CeTb increases continually from 0 % to 20 % for the Conformal Phosphor Packaging (CPP) and 0 % to 1.0 % for the Phosphor In-cup Packaging (IPP). Referring to the simulation results in Fig. 6, it is clear that the lumen output grows remarkably with increasing of the concentration of CeTb.

In summary, the MCW-LED packages with better-Correlated Color Temperature (CCT) uniformity could

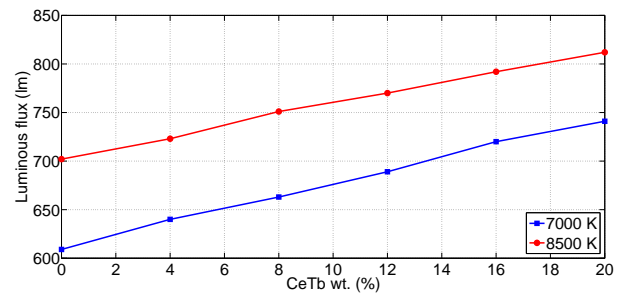


(a) CPP.

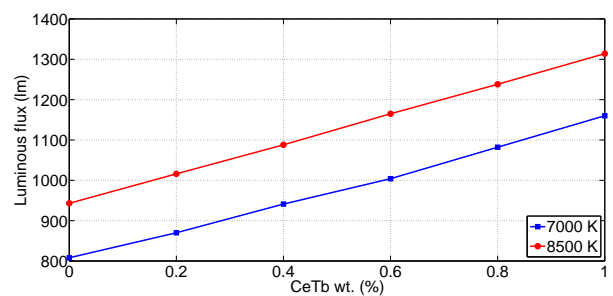


(b) IPP.

**Fig. 5:** The angular CCT peak-valley (P-V) deviation with various CeTb concentration.



(a) CPP.



(b) IPP.

**Fig. 6:** The lumen output at average CCTs 7000 K and 8500 K with different CeTb concentration.

be accomplished. However, referring to the accomplished simulation results in Fig. 6 and Fig. 7, it can be found that the higher CeTb concentration is involved, the higher the luminous flux, but less CRI can be obtained for both CPP and IPP MCW-LEDs.

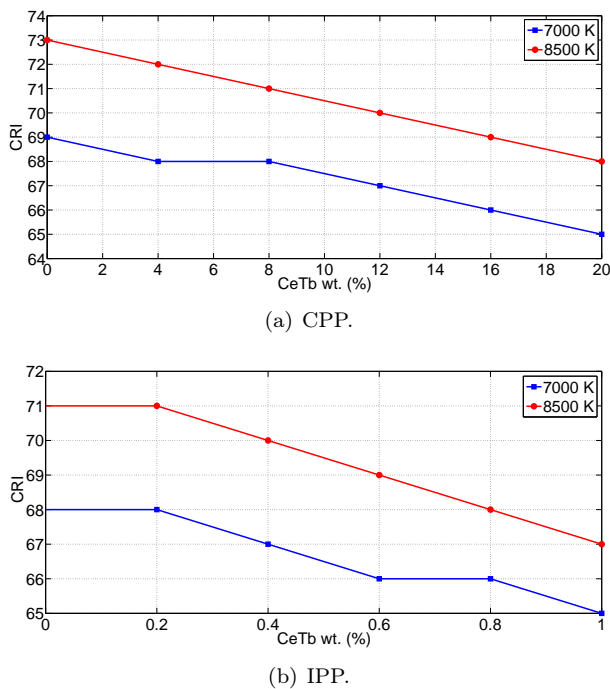


Fig. 7: The color rendering index at average CCTs 7000 K and 8500 K with different CeTb concentration.

## 4. Conclusion

In this paper, the green CeTb phosphor is proposed for enhancing the spatial color uniformity and the luminous efficiency of both CPP and IPP MCW-LED lamps. This study provided that with growing concentration of green CeTb phosphor the ACU and the lumen output of MCW-LED lamps increased significantly in comparison with the related works. Although, decreasing CRI with increasing concentration of the green CeTb phosphor is a limitation of this research. This study is the first step towards enhancing our understanding of green CeTb phosphor effect on the lighting performance of MCW-LED lamps. In the future work, the influence of green CeTb size on lighting performance and how to increase CRI of MCW-LED lamps with using green CeTb phosphor must be investigated.

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