

# Excellent Luminous Efficacy and Color Homogeneity of White Light-Emitting Diodes with $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$ Phosphor

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**Abstract.** In this paper, we focus on researching the method, which the color homogeneity and the lumen output of multi-chip white LED lamps (MCW-LEDs) need to support for increasing the efficiency. The successful results can be achieved by mixing the green  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  phosphor with their phosphor compounding. Through experiment results, we assert that the MCW-LEDs can achieve the significant consequence in performance by following that method and it is also again confirmed that when the concentration of  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  has tendency to increase, which impulse the development of the color uniformity and the luminous efficacy of MCW-LEDs with average correlated color temperatures (CCT) of 8500 K, while the color quality scale shows signs of gradual decline. It is not difficult to gain incredible presentation of MCW-LEDs if we are clever in choosing the suitable concentration and size of  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$ .

## 1 Introduction

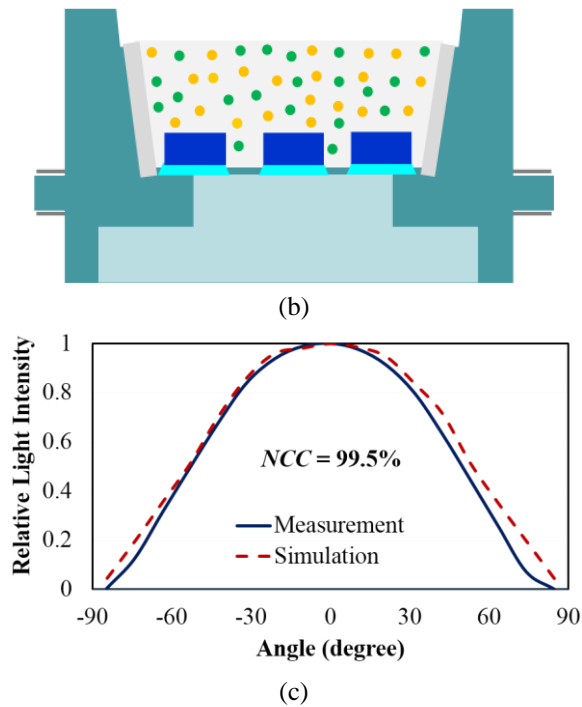
In recent years, the study which scientists concerned the most is that how to enhance the light performance of white LED packages effectively and uninterruptedly. In which, the matter which concerned as the important one related to white LED lamps is lumen output and color [1-10]. After many efforts in experiments and researches, Anh with his colleague have finally recognized that when  $\text{SiO}_2$  particles is poured into  $\text{YAG}:\text{Ce}^{3+}$  phosphor compounding, it will give us an unanticipated result [11]. The quality of multi-chip white LED lamps could significantly promote as possible through that process. In order to create a compounding which is able to absorb the blue light of the blue chips and emits the yellow light, the yellow  $\text{YAG}:\text{Ce}^{3+}$  phosphor material has to rely on the silicone glue to mix together for the creation of compounding. The white light is a part of component obtained from the process of mixture of the colors. As a result, the emitted normal light tends to be more bluish when it comes to the surface of LED, while its position is in nearly parallel to the LED surface it will bring the tendency of more yellowish. Hence, if light intensity distributions is different, it can create a ring which is more likely yellow [12-20].

By using the method of optimization for phosphors or optical structures of white LEDs, it will help the white light quality and lumen output have a positive aspect. In addition,  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  particles is known as efficient green component of trichromatic lamp phosphor, which includes so many special features like high quantum efficiency, stability at high temperature and because of these features, it becomes more and more popular [21].

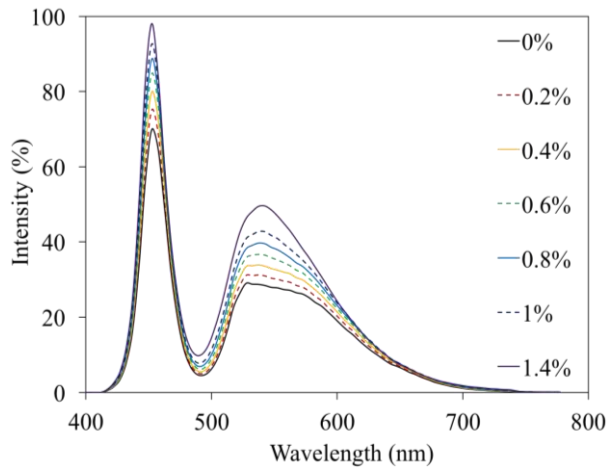
Moreover,  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  is applied particularly for very high-loading and long life-time fluorescent lamps. Therefore, it is one of the most popular commercialized oxide phosphors. In this paper, we definitely suggest and employ the green  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  phosphor in the phosphor compounding of MCW-LEDs to help color uniformity and lumen output attain the best result. The conducted research is a 3-stage process: (1) Constructing model of MCW-LEDs; (2) Putting  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  into the phosphor compounding of the simulated MCW-LEDs; (3) Analyzing the effects of  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  concentration on the lighting performance, including the emission spectra and the scattering. The investigated results give us a conclusion that if green  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  and yellow  $\text{YAG}:\text{Ce}^{3+}$  phosphors are mixed together to be a perfect compounding, color uniformity and lumen output can be attained the best quality.



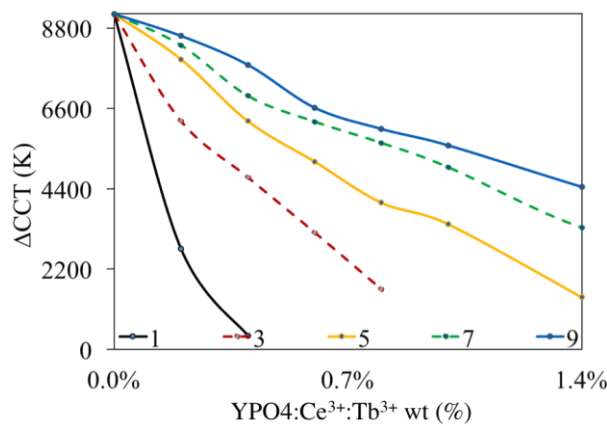
(a)



**Fig. 1.** (a) Photograph of an employed MCW-LED, (b) In-cup phosphor geometry, (c) The calculation of normalized cross correlation (NCC).



**Fig. 2.** Emission spectra of multiple phosphors.

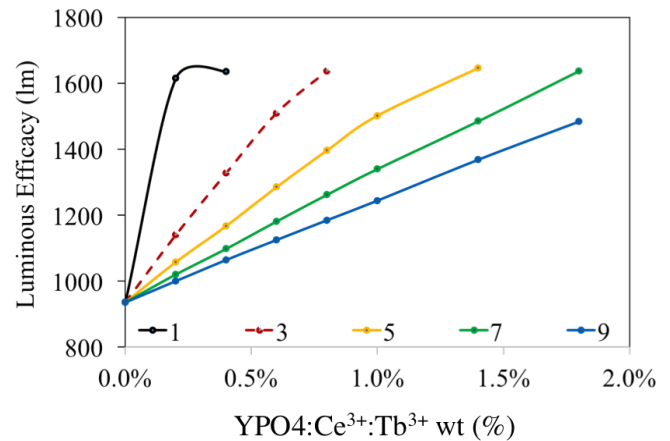


**Fig. 3.** The CCT peak-valley deviation as a function of the concentration and size of  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$ .

## 2 Simulation and discussion

According to LightTools 8.1.0 program and Monte Carlo method, the phosphor layer of real MCW-LEDs is carried out simulation with flat silicone layer. We carry out the modeling process through 2 main periods: (1) the mechanical structures and optical properties of MCW-LED lamps must be set and built. (2) Next, after completing the first step we continue monitoring the optical influences of phosphor compounding through the diversity of  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  concentration. The results of the NCC related experiments are shown in Fig. 1(c). The NCC values is higher than 99.5% for both CPG and IPG, so the WLED models are appropriate to be used in the computational simulation.

In order to understand the influence of  $\text{YAG}:\text{Ce}^{3+}$  and  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  phosphor compounding on the performance of MCW-LED lamps, we must have been carried out some experiments. In there, in-cup phosphor compounding is considered to clarify, which has average CCTs at 8500 K. In figure 1(top), there is a clearly description about MCW-LED lamps with conformal phosphor compounding having average CCTs of 8500 K. It also indicates the simulation of MCW-LEDs, which the components do not contain  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$ . 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, whose thickness is fixed at 0.08 mm, covers nine chips. Each LED chip with the square base area of  $1.14 \text{ mm}^2$  and the height of 0.15 mm is attached to the cavity of the reflector. The radiant flux of each blue chip is 1.16 W and 453 nm is the peak wavelength.



**Fig. 4.** Luminous efficacy as a function of the concentration and size of  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$ .

Figure 2 detailed displays the emission spectra of in-cup phosphor compounding with different ranges of  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  concentration and it is sometimes even up to 1.4%. Through this chart, we can know clearer that the lumen output of MCW-LEDs may be enhanced after  $\text{YPO}_4:\text{Ce}^{3+}:\text{Tb}^{3+}$  particles are poured together into phosphor compound.

In this research, it is really important and necessary for meeting the demand of the LED product specification, so MCW-LED needs requesting to work in the scope of

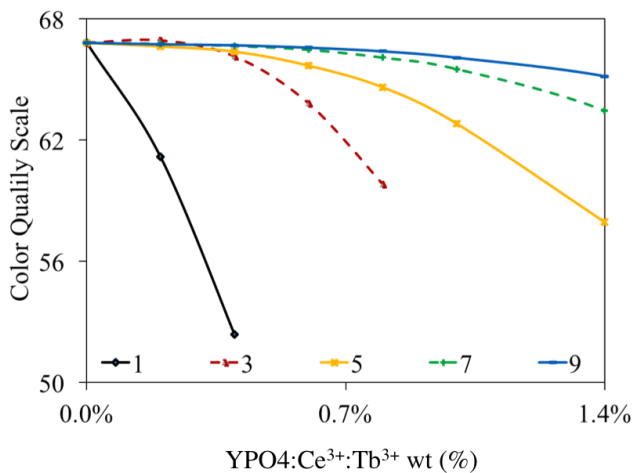
average CCTs of 8500 K. In addition, when the concentration of the green YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> phosphor grows, that of yellow YAG:Ce<sup>3+</sup> phosphor must be obviously reduced because of the maintaining the average CCTs of 8500 K. The weight percentage of the LED phosphor layer can be expressed as:

$$\sum W_{pl} = W_{yellow\ phosphor} + W_{silicone} + W_{green\ phosphor} = 100\% \quad (1)$$

In this formula,  $W_{silicone}$ ,  $W_{yellowphosphor}$  and  $W_{greenphosphor}$  are the weight percentage of the silicone glue, the yellow YAG:Ce<sup>3+</sup> phosphor and the green YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> phosphor in turn.

The simulation receives the results, which the angular color deviation of MCW-LED is in the appearance and absence of YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> are shown in Figure 3. It can be observed that the CCT peak-valley deviation reduces significantly with the involving of YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup>. It means that the spatial color distribution of MCW-LEDs with YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> is much flatter than that in lacking of YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup>.

If we just optimize an element, the optical system can weakly achieve in other aspects. In particular, we cannot achieve the best CQS values and the efficiency of the white LED package at the same time, there is only aspect achieving results as desired. The answer is that if we need to collect a good CRI, it has to have a broad source spectrum and efficiency is maximized at monochromatic radiation with a wavelength of 555 nm. In this study, CQS, luminous flux and CCT P-V deviation values are three competing properties. About the simulation results in Figure 4 and Figure 5, it can be found that the lumen output grows with the concentration of YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup>. Besides, the results also show that the more YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> concentration involved, the higher luminous flux we get, but the CQS tends to be less. Moreover, the concentration of YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> develop in a downward trend but it is insignificant, MCW-LED packages could be accomplished with better correlated color temperature uniformity and higher luminous flux.



**Fig. 5.** Color quality scale as a function of the concentration and size of YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup>.

### 3 Conclusion

In this study, the main purpose which all the paper we focus on study is the effect of the green YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> phosphor and its ability in improving the quality of both the color uniformity and the lumen output of white LED packages. Firstly, the color uniformity can be significantly enriched regardless of the average CCT value and the phosphor geometry if it obeys the Mie-scattering theory. This can be achieved due to the compensation of light-scattering to white LED packages. Next by applying Monte Carlo simulation, we demonstrated that the change of lumen output depends on the YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> concentration. Indeed, the lumen output grows with the YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> concentration. Finally, the paper proves the implication that YFQ: Ce<sup>3+</sup>: Tb<sup>3+</sup> phosphor application is a promising solution for developing the pc-WLEDs, and for all the manufacture of white LED packages.

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