# Enhancement of Color Rendering Index for White Light LED Lamps by Red $Y_2O_3$:$Eu^{3+}$ Phosphor

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***Abstract.*** *We present an application of the red $Y_2O_3$:$Eu^{3+}$ dopant phosphor compound for reaching the color rendering index as high as 86. The Multi-Chip White LED lamps (MCW-LEDs) with high Correlated Color Temperatures (CCTs) including 7000 K and 8500 K are employed in this study. Besides, the impacts of the $Y_2O_3$:$Eu^{3+}$ phosphor on the attenuation of light through phosphor layers of the various packages is also demonstrated based on the Beer-Lambert law. Simulation results provide important conclusion for selecting and developing the phosphor materials in MCW-LEDs manufacturing.*

## Keywords

***Beer-Lambert law, Color Rendering Index, pc-WLEDs, $Y_2O_3$:$Eu^{3+}$.***

## 1. Introduction

There are many benefits of MCW-LEDs to consumers such as high brightness, low power consumption, long lifetime, fast response, climate impact resistance [1]. Correspondingly, MCW-LEDs are considered to be key lighting devices to replace traditional lamps. Luminous output and Correlated Color Temperature (CCT) uniformity are two main factors of white LED lamps. By adding $SiO_2$ powder having the suitable size and concentration, some researchers have reduced spatial CCT deviation without decreasing lumen output significantly. The lumen output of MCW-LEDs can be enhanced significantly after adding the green $Ce_{0.67}$ $Tb_{0.33}$ $MgAl_{11}$ $O_{19}$:Ce, Tb phosphor to MCW-LEDs [2].

Furthermore, we cannot but mention the Color Rendering Index (CRI) that is considered as one important characteristic of MCW-LEDs. Several previous studies have applied methods that consist of mixing red-phosphors or doping red LEDs to compensate red-light to MCW-LEDs [3], [4], [5], [6], [7]. Besides, Won et al. presented high CRI multi-chip white LEDs, combining blue LEDs and green $(Ba,Sr)_2SiO_4$:$Eu^{2+}$ and red $CaAlSiN_3$:$Eu^{2+}$ phosphors with the different packages. By doping the missing red component in phosphor-converted MCW-LEDs (pc-WLEDs), the CRI of MCW-LEDs can be enhanced to more than 80, which is an important goal [2].

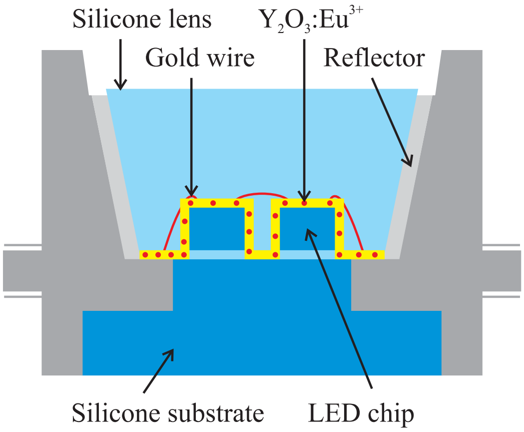
Red $Y_2O_3$:$Eu^{3+}$ phosphor is one of cathodoluminescent phosphors, which is employed widely in color displays as a red-light-emitting component. However, $Y_2O_3$:$Eu^{3+}$ phosphor has not many applications for improving CRI as yet.

In this paper, we introduce the impacts of $Y_2O_3$:$Eu^{3+}$ phosphor particles in multi-chip white light LEDs with conformal phosphor or in-cup phosphor packages to enhance color rendering ability. It has been found that the participation of $Y_2O_3$:$Eu^{3+}$ phosphor particles can dominate the red-light emitting event in pc-WLEDs, so that the LED light distribution can be free from the dispersion incurred by LED packages to yield higher Color Rendering Index.

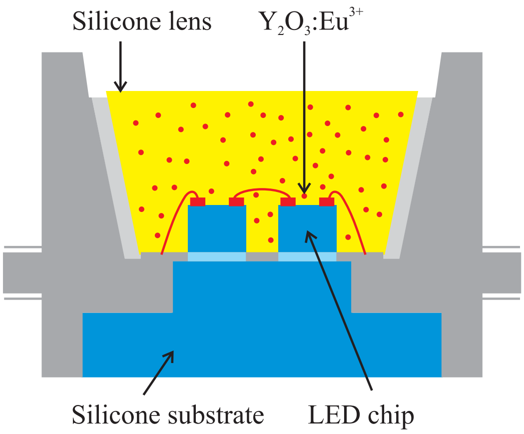
We have divided the work processes into three main stages. The precise MCW-LEDs physical model having average CCTs of 7000 K and 8500 K has been conducted by LightTools software at first. Then, the transmission of light has been decreased after mixing $Y_2O_3$:$Eu^{3+}$ particles, which has demonstrated the Beer-Lambert law. Finally, we have investigated the effects of $Y_2O_3$:$Eu^{3+}$ phosphor particles on the color rendering ability of MCW-LEDs according to the simulation results. Based on the results, the proposed method of doping certain amounts of $Y_2O_3:Eu^{3+}$ in the LED packages can improve their CRI significantly.

## 2. Simulation

The pc-WLEDs is covered by flat silicone layer, which is simulated by using LightTools 8.1.0 program. The key work consists of pc-WLEDs construction and phosphor concentration adjustment. Firstly, the structures of pc-WLEDs such as the Conformal Phosphor Package (CPP) and the In-cup Phosphor Package (IPP) are introduced with five CCTs of 7000 K and 8500 K, see Fig. 1. Secondly, it is necessary to keep the MCW-LEDs work at mean CCTs from 7000 K to 8500 K for achieving the LED product specification. If the weight percentage of the red $Y_2O_3:Eu^{3+}$ phosphor increases, that of yellow YAG:Ce phosphor needs to be decreased to maintain the mean CCT values.




(a) the conformal phosphor package




(b) the in-cup phosphor package

**Fig. 1:** Illustration of MCW-LEDs.

The optical properties of reflector of CPP and IPP are similar. The depth, inner, and outer radius of the reflector are 2.07 mm, 8 mm and 9.85 mm, respectively. The CPP and the IPP, with the fixed thickness of 0.08 mm and 2.07 mm in turn, cover the nine chips. The blue Led chip has a dimension of $1.14 \times 0.15$ mm. The radiant flux of each blue chip is 1.16 W, and the peak wavelength is 453 nm. At the CPP displayed in Fig. 1(a), its phosphor layer is coated conformally on nine LEDs. As for the IPP, its phosphor layer is located in the silicone lens, as displayed in Fig. 1(b).

The absorption, emission and scattering of both YAG:Ce and $Y_2O_3:Eu^{3+}$ phosphor particles, with the peak wavelengths including blue of 453 nm and green-yellow of 555 nm, can be computed by Mie-scattering theory [2]. The phosphor layers consist of YAG:Ce and $Y_2O_3:Eu^{3+}$ powders and the silicone matrix. Their refractive indexes are 1.83, 1.93 and 1.50, respectively. Meanwhile, the mean radii of the phosphor powders are 7.25 µm, which conforms the real particle size.

## 3. Color Rendering Index

In order to verify the improvement of CRI using $Y_2O_3:Eu^{3+}$ phosphor, we switch the average CCT among the values of 7000 K and 8500 K and change $Y_2O_3:Eu^{3+}$ weight. The corresponding values of CRI are then calculated and displayed on Fig. 2. Figure 2(a) illustrates the impact of $Y_2O_3:Eu^{3+}$ concentration on CRI of CPP structures. It can be observed that the CRI grows with the weight percentage of $Y_2O_3:Eu^{3+}$ phosphor in the continuous range from 0 % to nearly 10 %. The highest color rendering ability is obtained with the $Y_2O_3:Eu^{3+}$ weight range from 8 % to 12 %. In particular, optimal color rendering index that can be achieved exceeds the value of 86 in this case. As for IPP structure, the $Y_2O_3:Eu^{3+}$ concentration ranges continuously from 0 % to approximately 0.4 %. From 0.3 % to 0.4 %, the CRI has a decreasing tendency with the increasing of $Y_2O_3:Eu^{3+}$ weight beyond a point where the red-light starts to be over-dominant, causing color rendering ability to reduce.

The highest color rendering ability with the different CCTs can be obtained when the $Y_2O_3:Eu^{3+}$ percentage ranges from 0.24 % to 0.3 %, as shown in Fig. 2(b). The optimal color rendering index of MCW-LEDs can exceed 84 in this case, which is 25.8 % higher than that of the non $Y_2O_3:Eu^{3+}$ case, i.e. When the $Y_2O_3:Eu^{3+}$ concentration is equal to 0 %. In summary, with the simulated results of CRI, we can demonstrate that the $Y_2O_3:Eu^{3+}$ phosphor having proper concentration can be used for increasing the CRI.

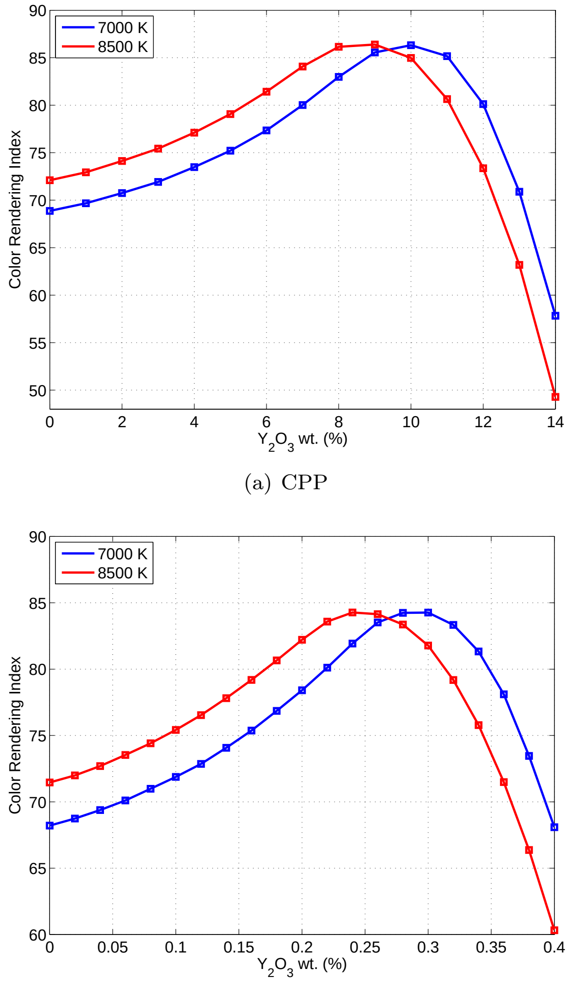



**Fig. 2:** The color rendering index at average CCTs of 7000 K and 8500 K with various $Y_2O_3:Eu^{3+}$ weight with two phosphor geometries.

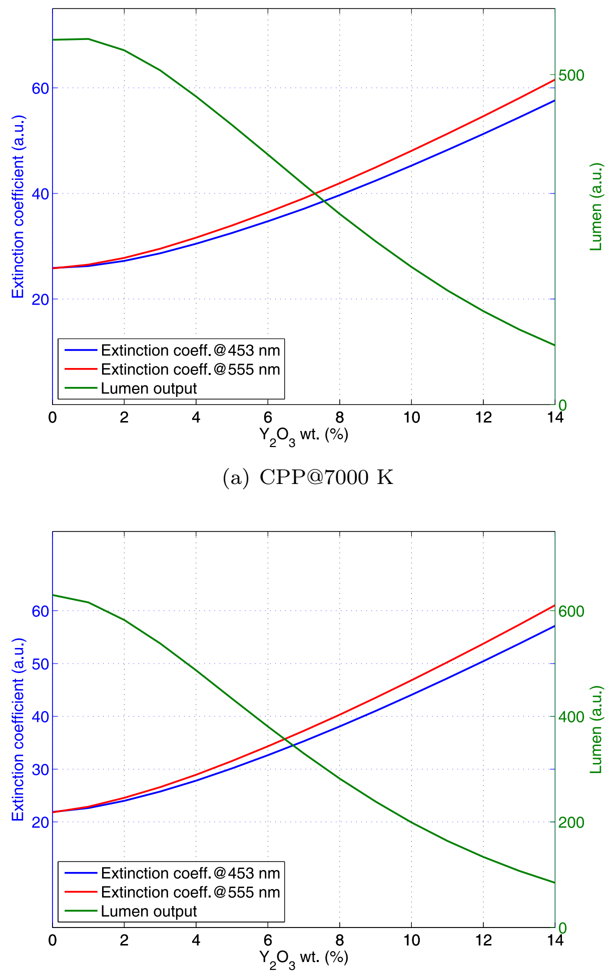



**Fig. 3:** Luminous flux according to computed extinction coefficient of CPPs.

# 4. Luminous Flux

The effect of $Y_2O_3:Eu^{3+}$ concentration in phosphor compound on the lumen output is also verified together with the CRI, as shown in Fig. 3. The weight percentage of phosphor compound was varied continuously from 0 % to 14 % and to 0.4 % for CPP and IPP, respectively. At low $Y_2O_3:Eu^{3+}$ concentration regime, the extinction coefficient tends to reduce, which results in the enhancement of luminous output. Meanwhile, the luminous flux decreases with the $Y_2O_3:Eu^{3+}$ weight enhancement due to the increase of extinction coefficient.

To verify these results, the relationship of luminous output to the $Y_2O_3:Eu^{3+}$ weight can be formulated according to Mie-scattering theory. The depletion of light is calculated by the Beer-Lambert law:

$$I = I_0 e^{-\mu_{ext} L}, \tag{1}$$

where $I$ is the transmitted light power, $I_0$ is the incident light power, $\mu_{ext} = N \cdot C_{ext}$ is the extinction coefficient, $L$ is the path length and $N$ is the number of particles per cubic millimeter.

According to Mie-scattering theory, the extinction cross section $C_{ext}$ of phosphor particles can be characterized by the following relationship:

$$C_{ext} = \frac{2\pi a^2}{x^2} \sum_{n=1}^{\infty} (2n+1)\mathrm{Re}(a_n + b_n), \tag{2}$$

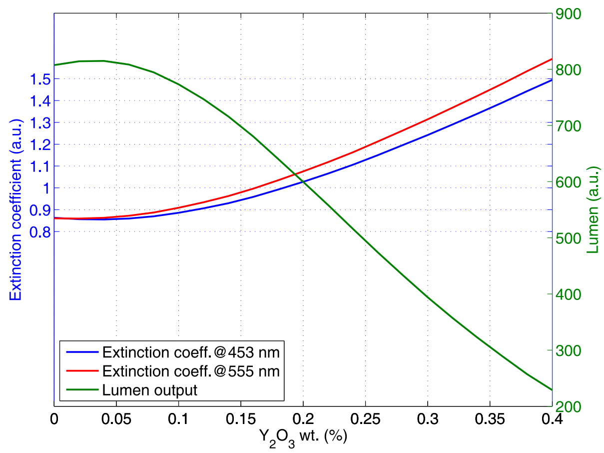
where $x = 2\pi a/\lambda$ is the size parameter, $a_n$ and $b_n$ are the expansion coefficients with even symmetry and odd symmetry, respectively. The parameters $a_n$ and $b_n$ are defined as:

$$a_n(x,m) = \frac{\psi_n'(mx)\psi_n(x) - m\psi_n(mx)\psi_n'(x)}{\psi_n'(mx)\xi_n(x) - m\psi_n(mx)\xi_n'(x)}, \tag{3}$$

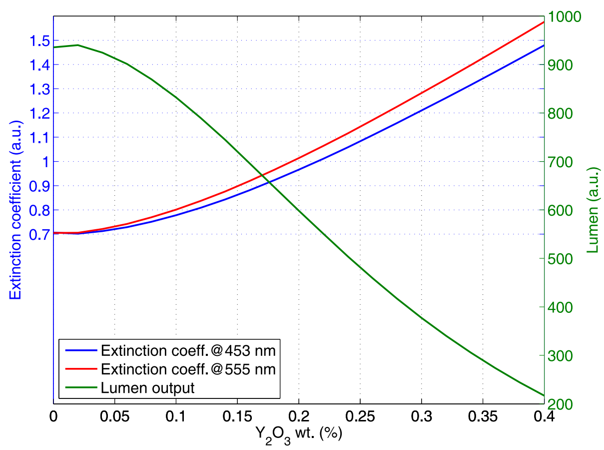
$$b_n(x,m) = \frac{m\psi'(mx)\psi_n(x) - \psi_n(mx)\psi_n'(x)}{m\psi_n'(mx)\xi_n(x) - \psi_n(mx)\xi_n'(x)}, \tag{4}$$

where $a$ is the spherical particle radius, $\lambda$ is the relative scattering wavelength, $m$ is the refractive index of scattering particles, and $\psi_n(x)$ and $\xi_n(x)$ are the Riccati–Bessel functions. The extinction coefficient of the red $Y_2O_3:Eu^{3+}$ phosphor is verified for two distinct wavelengths, 555 nm and 453 nm, which are the emission peaks of the YAG:Ce phosphor and the LED chips, respectively.

The variation of the mentioned parameters with respect to the $Y_2O_3:Eu^{3+}$ concentration according to the above equations are displayed in Fig. 3 and Fig. 4. The simulation results of luminous flux for CPP as shown in Fig. 3 are compared with those for IPP as demonstrated in Fig. 4. It is indicated that the higher lumen output should occur at low $Y_2O_3:Eu^{3+}$ concentration, which corresponds to the lower extinction coefficient value. These results can be employed to estimate the influence of $Y_2O_3:Eu^{3+}$ concentration on the lumen output from the pc-WLEDs.




(a) IPP@7000 K




(b) IPP@8500 K

**Fig. 4:** Luminous flux according to computed extinction coefficient of IPPs.

# 5. Conclusion

Summary, both the CRI and the lumen output of MCW-LEDs depend on the red $Y_2O_3:Eu^{3+}$ phosphor concentration. Firstly, it is noted that the CRI can be enhanced to 86 and more regardless of the mean CCTs and the phosphor geometries. Next, the luminous flux has a decreasing tendency at large weight range due to the enhancement of the extinction coefficient. However, it is noticeable that the lumen output can be grown after adding $Y_2O_3:Eu^{3+}$ with low weight range. Finally, the paper proves the implications of $Y_2O_3:Eu^{3+}$ phosphor application for developing the pc-WLEDs of MCW-LEDs manufacturing.

# References


[1] ZHENG, H., X. B. LUO, R. HU, B. CAO, X. FU, Y. WANG and S. LIU. Conformal phosphor coating using capillary microchannel for controlling color deviation of phosphor-converted white light-emitting diodes. *Optics Express*. 2012, vol. 20, iss. 5, pp. 5092–5098. ISSN 1094-4087. DOI: 10.1364/OE.20.005092.

[2] LIU, S. and X. B. LUO. *LED Packaging for Lighting Applications: Design, Manufacturing and Testing*. Hoboken: John Wiley&Sons, 2011. ISBN 978-0-470-82840-3.

[3] LIU, Z. Y., S. LIU, K. WANG and X. B. LUO. Optical Analysis of Color Distribution in White LEDs with Various Packaging Methods. *IEEE Photonics Technology Letters*. 2008, vol. 20, iss. 24, pp. 2027–2029. ISSN 1041-1135. DOI: 10.1109/LPT.2008.2005998.

[4] LIU, Z. Y., S. LIU, K. WANG and X. B. LUO. Analysis of Factors Affecting Color Distribution of White LEDs. In: *International Conference on Electronic Packaging Technology & High Density Packaging*. Shanghai: IEEE, 2008, pp. 386–393. ISBN 978-1-4244-2740-6. DOI: 10.1109/ICEPT.2008.4607013.

[5] SOMMER, C., F. REIL, J. R. KRENN, P. HARTMANN, P. PACHLER, H. HOSCHOPF and F. P. WENZL. The Impact of Light Scattering on the Radiant Flux of Phosphor-Converted High Power White Light-Emitting Diodes. *Journal of Lightwave Technology*. 2011, vol. 29, iss. 15, pp. 5145–5150. ISSN 0733-8724. DOI: 10.1109/JLT.2011.2158987.

[6] CHIEN, W. T., C. C. SUN and I. MORENO. Precise optical model of multi-chip white LEDs. *Optics Express*. 2007. vol. 15, iss. 12, pp. 7572–7577. ISSN 1094-4087. DOI: 10.1364/OE.15.007572.

[7] WANG, K., S. LIU, X. B. LUO, Z. Y. LIU and F. CHEN. Optical Analysis of A 3W Light-Emitting Diode (LED) MR16 Lamp. In: *International Conference on Electronic Packaging Technology & High Density Packaging*. Shanghai: IEEE, 2008, pp. 1–5. ISBN 978-1-4244-2740-6. DOI: 10.1109/ICEPT.2008.4607028.

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