Improving Lighting Performance of High Color Temperature White LED Packages Using (La,Ce,Tb)PO_4:Ce:Tb Phosphor

Thi Phuong Thao NGUYEN[1,2] *Doan Quoc Anh NGUYEN*[1,*], *Miroslav VOZNAK*[2], *Van Tho LE*[3]

[1]Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[2]Department of Telecommunications, Faculty of Electrical Engineering and Computer Science, VSB–Technical university of Ostrava, 17. listopadu 15, 708 33 Ostrava, Czech Republic
[3]Institute of Tropical Biology, Vietnam Academy of Science and Technology, Ho Chi Minh City, Vietnam

*nguyendoanquocanh@tdt.edu.vn
(Received: 31-August-2017; accepted: 26-October-2017; published: 30-Novermber-2017)
DOI: http://dx.doi.org/10.25073/jaec.201712.81

Abstract. *Enhancement of the color uniformity, the lumen output of the multi-chip white LED lamps (MCW-LEDs) at high color correlated temperature is a big challenge for researchers. However, an innovative LED lamp designed with a phosphor compounding, which combines (La,Ce,Tb)PO_4:Ce:Tb (LaTb) green phosphor with YAG: CE yellow phosphor, is proposed as an optimal solution to this requirement. Index, using LaTb green phosphor into MCW-LEDs could bring a superior optical performance for MCW-LEDs. It is found that the lumen output of this new MCW-LED at a high color temperature of 8500 K significantly improves up to 1600 lm compared to MCW-LEDs without LaTb phosphor. The simulation results demonstrated that the CCT deviation sharply decreases from 9000 to 1000 at the LaTb concentration range from 0 to 1.8 %, while the Color Rendering Index ability (CRI) and the Color Quality Scale (CQS) slightly decrease. To obtain the highest lumen output and the best color uniformity, the particle size range within 6 – 8 μm should be suggested.*

Keywords

Color quality, (La,Ce,Tb)PO_4:Ce:Tb, luminous flux, multi-chip white LED lamp.

1. Introduction

Recently, White Light Emitting Diodes (W-LEDs) with a potential flexibility and dominant functions is becoming an important role in our life in illumination applications such as general lighting, medical, lifestyle products [1]. One of the most popular methods of the white light emitting diode technology includes the employment of multiple monochromatic LED chips or the combining blue light emitted from the LED chips with YAG: Ce phosphor to produce white light that is called phosphor converted LED (pc-LEDs). However, the obtained results of lumen output and angular color uniformity are still low due to the intensive reflection and the reabsorption of light going back to the package. Therefore, the pursuit of W-LEDs with high luminous efficiency, excellent color uniformity, good CRI was widely developed in recent years [2]. LED with remote phosphor structure designed, in which the phosphor layer placed far away from the chip can improve the loss of backscattered light inside LED chip [3]. Although the remote phosphor structure brings the luminous efficiency higher than the dispensing and conformal structure, it is difficult in manufacturing technique the concave surface of this structure resulting in a non-uniform phosphor thickness. Moreover, the luminous efficiency, uniform color distribution of MCW-LEDs hardly fulfill the different requirements of many illumination applications. As a development, the remote phosphor structure is optimized by design with the concentric green, red phosphor rings separated to reduce the backscattering problems. The extraction efficiency, the color rendering property of the proposed MCW-LEDs are higher than MCW-LEDs having a mixed phosphor layer [4]. A different phosphor configuration, which has a novel double remote micro-patterned phosphor film, is used to enhance the color uniformity of MCW-LEDs [5]. On the other hand, the configuration of LED's lens is extensively studied to optimize uniform illumination and the illumination efficiency. Therefore, there is an exploration of new discoveries about len structure to optimize the light quality of MCW-LEDs. A len with a freeform microlens array or the droplet evaporation structure or a free-form secondary lens structure exhibits better optical efficiency than traditional lens [6] and [7]. Also, the luminescent material is one of the important factors that strongly affect the performance of the multi-chip MCW-LEDs, and hence it is studied for purpose overcoming poor light extraction and color uniformity problem. For example, Kaur [8] has presented a new research about $LaAlO_3$ phosphor that generates the yellow-orange-red emission intensity stronger when combining this phosphor with the blue LEDs. Another study found that the use of the different structures of green $(Ba, Sr)_2SiO_4:Eu^{2+}$ and red $CaAlSiN_3:Eu^{2+}$ phosphor compounding with blue LEDs can help achieve better LED performance [9]. Because of the great potential of this luminescent phosphor material, they were continuously researched and developed.

Although the above approaches are expected to improve the performance of MCW-LEDs, the luminous efficiency and the angular color uniformity of white LEDs are not fully satisfied many different illumination applications, as well as extensive demands in the commercial, LED lighting market. Besides, the papers mainly research on white LED lamps with single-chip at low color correlated temperature. Moreover, in order to satisfy the competitiveness in lighting market and offer better light quality, advanced studies should be extensively conducted to find the most optimal configuration of LEDs or new phosphor materials that help increase the luminous intensity and color uniformity at such high temperatures.

Hexagonal prism $(La,Ce,Tb)PO_4$ green phosphor is frequently employed for very high loading and durable fluorescent bulbs due to its higher quantum efficiency, chemical and thermal stability of this material. $(La,Ce,Tb)PO_4$ composition obtains from chemical processes of the materials such as citric acid $(NH_4)_2HPO_4$, $Ce(NO_3)_3.6H_2O$, HNO_3, $La(NO_3)_3$, $Tb(NO_3)_3$. Ce^{3+} ion can act as an efficient sensitizer to Tb^{3+} and with the appropriate increase of Ce^{3+} concentration will improve the thermal quenching properties of LaTb phosphor. Therefore, this phosphor compounding is considered to be an efficient host candidate for good optical performance of the MCW-LEDs at high color correlated temperature.

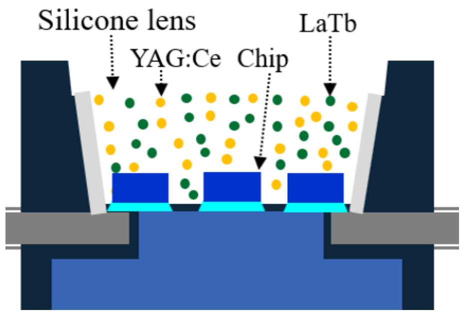
In this paper, we propose adding LaTb green luminescent phosphor to yellow YAG:Ce phosphor compound of the MCW-LEDs to optimize its light extraction, the CCT uniformity and CRI at high color correlated temperature. From the obtained simulation results, we discovered that LaTb green phosphor does not only improve the luminescent properties in traditional fluorescent lamps at such high temperature as published in a previous paper [10] but also it could produce the great enhancement for color uniformity and lumen output in in-cup phosphor package of the MCW-LEDs. The weight percentage and size of LaTb phosphor particle are varied from the simulation process to examine closely its effect on the optical performance of the MCW-LEDs. The optical properties of LaTb and YAG:Ce phosphor compounding are studied by analyzing light absorption, scattering as well as light conversion in LEDs at high correlated color temperature. In other words, we carried out simulations and calculations to discover the positive effect of concentration and size of LaTb green luminescent phosphor on luminous flux, angular color distribution, CRI and CQS at a high color temperature of 8500 K MCW-LEDs.

2. Simulation and Computation

In order to investigate the influence of LaTb phosphor on the performance of the MCW-LEDs at the high correlated temperature of 8500 K. The MCW-LED with in-cup phosphor structure is simulated by using the LightTools 8.1.0 program and Mie-theory to analyze the scattering of phosphor particles. To obtain the precise simulation results about the effect of LaTb phosphor on MCW-LED, our study used the parameters of the real -world model of LED for simulation. Figure 1(a) shows an actual MCW-LED with in-cup phosphor package having average temperature of 8500 K. These parameters about structure of this real MCW-LED are employed for designing a simulated MCW-LED (see Fig. 1(a)). In the preparation process of the in-cup phosphor structure of MCW-LED, the LaTb and YAG: Ce phosphor compounding are mixed in silicon lens as shown in Fig. 1(b). Therefore, the phosphor layer of the MCW-LED consists of LaTb green phosphor, the yellow phosphor YAG:Ce and the silicone glue. The model structure as in Fig. 1(b) shows the components of simulated the MCW-LED including blue chips, a reflector cup, a phosphor layer and a silicone layer. A reflector with a 2.07 mm depth, a bottom length of 8 mm and a length of 9.85 mm at its top surface is bonded with these chips. The radiant power of each nice blue chip was designed with 1.16 W, a peak wavelength of 453 nm.

The radius of the green LaTb phosphor particles was changed from 1 μm to 10 μm. The LaTb phosphor particle density varies from 0 – 1.8 % in the simulation process to optimize color uniformity and lumen output efficiency. The refractive index of phosphor particle is set to be 1.85 and 1.83 for LaTb and YAG: Ce, respectively. To maintain the average CCT of white LEDs at

(a) A sample LED used in this study.



(b) The simulated the in-cup phosphor package.

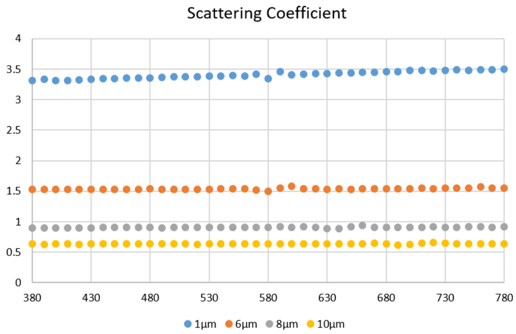
Fig. 1: Illustration of MCW-LEDs structure.

8500 K, YAG: Ce phosphor concentration needs to be appropriately changed with the concentration of LaTb green phosphor. To obtain the precise results about the effect of LaTb green phosphor on the optical performance o MCW-LED at high temperature, the optical simulation process is carried out with a change of LaTb particle size and density.

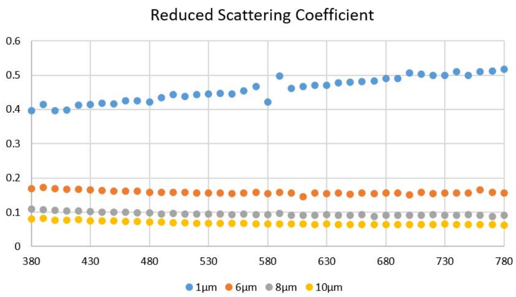
The scattering of LaTb phosphor particles was analyzed by using the Mie-theory. The optical constants of scattering coefficient $\mu_{sca}(\lambda)$ and reduced scattering coefficient $\delta_{sca}(\lambda)$ can be computed by the below expressions Eq. (1) and Eq. (2):

$$\mu_{sca}(\lambda) = \int N(r) C_{sca}(\lambda, r) dr, \qquad (1)$$

$$\delta_{sca}(\lambda) = \mu_{sca}(1 - g), \qquad (2)$$



(a) Scattering coefficient.



(b) Reduced scattering coefficient.

Fig. 2: The optical parameters of LaTb particles in the YAG:Ce phosphor compound of MCW-LEDs.

where $N(r)$ is the number density of particles, $C_{sca}(\lambda, r)$ is the scattering cross-section, g is anisotropy factor.

According to the obtained results as shown in Fig. 2(a), the scattering coefficient grows with the decrease of the size of LaTb particle, it means that the smaller phosphor particles scatter the incident light stronger and achieve a more color uniform compared with bigger particles. However, if the scattering coefficient is so high, the imbalance of the color spectrum of the emitting light will appear. This leads to the disadvantage in the light quality of MCW-LED. The highest color uniform can be achieved at a size of 1 µm. Generally, the scattering coefficient is the same with the wavelengths varied from 380 nm to 780 nm. The reduced scattering coefficient increases with the change of the wavelength at a small size of 1 µm as shown in Fig. 2(b). At the small size of 1 µm, the reduced scattering is slightly sensitive to the incident wavelength. Therefore, the optical performance of the MCW-LED in the wavelength range from 380 to 780 nm will not be stable. Thus, the use of LaTb particle size of 1 µm doesn't offer better color quality of the MCW-LED. Meanwhile, the reduced scattering doesn't change with the wavelength of the range within 6 – 10 µm.

3. Results and Discussion

The simulation results presented that LaTb particles offer a positive impact on the luminous flux of MCW-LEDs. It is found that the luminescence characteristics of LaTb green phosphors are strongly influenced by particle concentration and size. LaTb green luminescent phosphor is known to be a good candidate for enhancing the green light and thermal quenching phenomenon. Therefore, adding this particle in YAG:Ce phosphor layer will help LED achieve the higher brightness at the high temperature of 8500 K. In order to obtain precise results about optical features of LaTb, we carried out the simulations with the various concentrations from 0 to 1.8 % corresponding to each size with range within 1 – 10 µm. The lines of the graph representing the luminous flux sharply increase and can reach maximum value in the range of the concentration from 0 % up to 1.3 % and the size within 1 – 5 µm as depicted in Fig. 3. Luminous flux improves on all particle sizes when adding LaTb particles into phosphor compounding with increasing the concentration. As is known in many previous papers, the small particles usually provide less luminous flux than bigger ones due to the unwanted backward scattering inside MCW-LEDs [12]. It means that there is more probability of light trapped inside a package and less the light escaping from LEDs when the small particles are applied. Thereby, the light emission intensity decreases and hardly achieve the maximum value for small particles at a high correlated color temperature of 8500 K. However, LaTb green phosphor with dominant luminescent characteristics such as chemical and thermal stability can help overcome shortcomings about small particle sizes at high temperature to produce a higher lumen output for MCW-LEDs. With large particle size of 6 – 10 µm, the trend of light propagates stronger in the forward direction and weaker in the backward direction of LED chips; thereby the large particles show the advantages for lumen output. In another word, adding LaTb particles with different particle sizes to YAG:Ce phosphor offers a remarkable increase in the lumen output of the in-cup phosphor package at a high temperature of 8500 K.

Additionally, the effect of LaTb phosphor on angular color uniformity that representing by mean color deviation parameter (CCT) is simulated and analyzed. The concept of mean color deviation is determined by minus between CCT(Max) and CCT(Min) as following D-CCT = CCT (Max) - CCT (Min). Where CCT(Max), CCT(Min) is the maximum value, minimum value of CCT respectively. D-CCT parameter can be used to evaluate the influence of this phosphor on the color uniformity level of LEDs [13]. The high CCT of the package is attributed to the difficulty in obtaining a high color uniformity due to some issues of phosphor at this temperature. As a result, larger color deviation is usually generated by MCW-LEDs at this temperature. The color correlated temperature deviation obtained from the simulation process with various concentrations and sizes of LaTb particles in MCW-LEDs at 8500 K shows in Fig. 4. The CCT deviation significantly decreases when the concentration of LaTb particle increases in all different particle sizes. It means that LaTb particle shows a great effect on the color uniformity of the MCW-LEDs when it is added into phosphor compounding with the concentration range within 0 – 1.8 % and the size range from 1 µm to 10 µm.

Therefore, the excellent color uniformity capacity can be achieved in MCW-LEDs with this new method. The CCT deviation of white LEDs with smaller particles from 1 µm to 5 µm remarkably decreases from 4000 K to 500 K as shown in Fig. 4.

The CCT deviation value can reach the minimum value less than 500 K at 1 µm and concentration at 0.4 %. In the case of the particles with the bigger sizes from 5 µm – 10 µm, the tendency

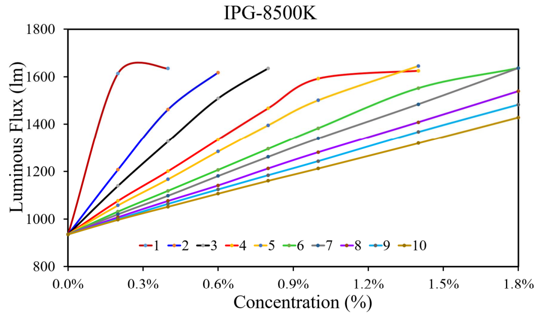


Fig. 3: The luminous flux of MCW-LEDs at average CCT 8500 K with different LaTb particle sizes and concentrations.

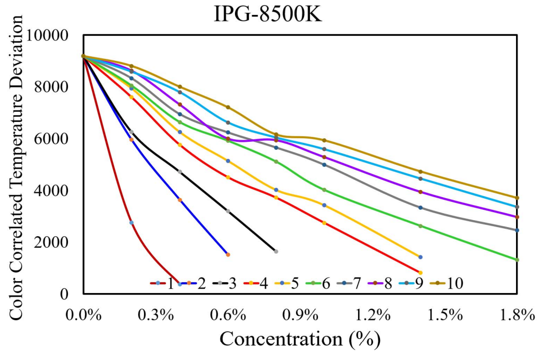


Fig. 4: The CCT deviation (ΔCCT) of MCW-LEDs at average CCT 8500 K with different LaTb particle sizes and concentrations.

of the color temperature deviation exhibits the features similar as the small particles. However, it is easy to realize that the lines of the graph for smaller particles drop faster than bigger ones, and thus, smaller particles can generate better scattering than bigger ones. This could be deduced that smaller particles of LaTb phosphor have more chance to scatter the incident lights in many different directions inside LEDs. As a result, the smaller particles make the color uniformity of MCW-LEDs flatter and better. The use LaTb phosphor into yellow YAG: Ce phosphor compounding makes the color uniformity better for all particles compared to that of non-LaTb case. The larger color temperature deviation is usually generated as MCW-LEDs illuminate at high CCT, but the LaTb phosphor compounding will help achieve a higher color uniformity at high CCT for all particle sizes with range within 1 – 10 µm compared to the phosphor compounding without LaTb particles.

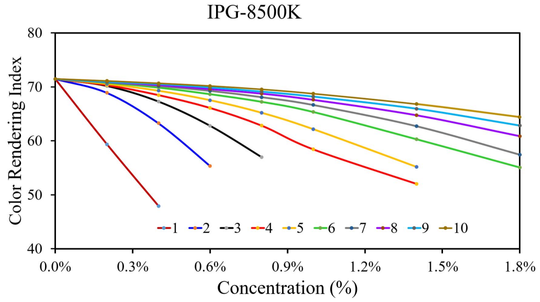


Fig. 5: The Color Rendering Index (CRI) value of MCW-LEDs at average CCT 8500 K with different LaTb particle sizes and concentration.

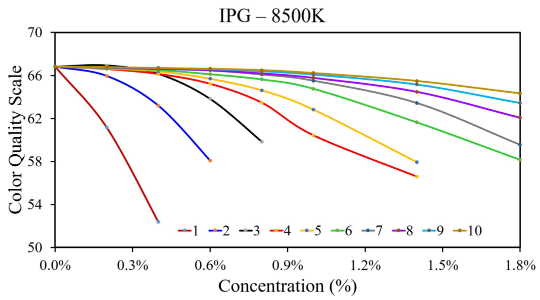


Fig. 6: The Color Quality Scale (CQS) value of MCW-LEDs at average CCT 8500 K with different LaTb particle sizes and concentrations.

Moreover, the effect of LaTb particles in the phosphor compounding of the MCW-LEDs on CRI, CQS is investigated in this paper. As shown in Fig. 5, the CRI value slightly decreases in size range from 6 μm to 8 μm. The reason is that adding LaTb green luminescent phosphor resulting in green light supplementation and deficiency of red components in the spectrum of the MCW-LEDs, at this moment decreasing the CRI. It is essential to have a broader spectrum of light sources to increase CRI, and thus, the maximum efficiency of the white LED wouldn't be able to achieve. The CQS index, which evaluates the overall color quality of the MCW-LEDs about color fidelity, chromatic discrimination, and observer preferences, shows slight decrement similarly as CRI at a concentration around 1.5 % and the particle 6 – 8 μm as Fig. 6.

Although LaTb particles from 1 μm to 5 μm help MCW-LEDs significantly enhance lumen output and color uniformity for the LaTb particles with the concentration of 1.5 % and size range within 6 – 8 μm should be the best choice. In this size and concentration range, the most optimal color uniformity and lumen output can achieve accompanying with the insignificant decrease of CRI, CQS values as well.

4. Conclusion

In this article, the effect of LaTb green luminescent phosphor on the MCW-LED performance at 8500 K is analyzed and demonstrated in detail. The optical simulation reveals that the LaTb particles can significantly improve both luminous flux and color uniformity at high color correlated temperature. We analyzed the effect of size and concentration of LaTb particle on CCT, luminous flux, CRI and CQS. For the particle sizes smaller than 5 μm, the lumen output and the color uniformity are remarkably enhanced with the adopting phosphor concentration smaller 1.5 %. Meanwhile, the concentration range within 0 – 1.8 % should be added for particle sizes from 6 μm to 10 μm. The optimal size and concentration of LaTb particles should be chosen from 6 μm to 8 μm and 1.5 % respectively. The lowest CCT value, the highest luminous flux accompanying with an insignificant decrease in CRI, CQS could be achieved in this range. It could be concluded that, by adding LaTb green phosphor with the concentration range within 0 – 1.8 % and the particle size of 6 – 8 μm into phosphor compounding can obtain better optical performance of white LEDs. Therefore, applying LaTb phosphor to the white MCW-LED package is a promising solution for development of LED illumination technology in the future.

Acknowledgment

This research is funded by Foundation for Science and Technology Development of Ton Duc Thang University (FOSTECT), website: http://fostect.tdt.edu.vn, under Grant FOSTECT.2017.BR.06.

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About Authors

Thi Phuong Thao NGUYEN was born in Quang Ngai province, Vietnam. She graduated from the University of Technology, Ho Chi Minh City, Viet Nam. She received her B.E. and M.E. degrees in automatic control engineering in 2006 and 2009, respectively. Now, She is teaching at the department of electrical and electronics engineering, Ton Duc Thang University, Ho Chi Minh city, Vietnam. Her research interests include an automatic control system and optoelectronics.

Doan Quoc Anh NGUYEN was born in Khanh Hoa province, Vietnam. He has been working at the Faculty of Electrical and Electronics Engineering, Ton Duc Thang University. Quoc Anh received his PhD degree from National Kaohsiung University of Applied Sciences, Taiwan in 2014. His research interest is optoelectronics (such as Multi-chip white light LEDs, free-form lens, optical material).

Miroslav VOZNAK (born in 1971) is an Associate Professor with the Department of Telecommunications, Technical University of Ostrava, Czech Republic and foreign professor with Ton Duc Thang University in Ho Chi Minh City, Vietnam. He received his Ph.D. degree in telecommunications in 2002 at the Technical University of Ostrava. He is a senior researcher in the Supercomputing center IT4Innovations in Ostrava, Czech Republic, a member of the Scientific Board of FEI VSB-TU Ostrava, editorial boards of several journals and boards of international conferences. Topics of his research interests are IP telephony, wireless networks, speech quality and network security.

Van Tho LE was born in Thanh Hoa province, Vietnam. He has been working at the Institute of Tropical Biology, Vietnam Academy of Science and Technology. He received his master degree from Ho Chi Minh City University of Science, Vietnam in 2017. His research interest is ecological engineering, optoelectronics.