Rev. Adv. Mater. Technol., 2022, vol. 4, no. 3, pp. 35–41 DOI: 10.17586/2687-0568-2022-4-3-35-41

Numerical Simulation of Light Extraction from Remote Phosphor LED

S.N. Lipnitskaya[1,*], I.I. Dudko[2,3], I.G. Smirnova[1]

[1] Laboratory of Single-Photon Detectors and Generators, ITMO University, Kronverkskiy pr., 49, lit. A, St. Petersburg, 197101, Russia

[2] École Centrale de Lyon, CNRS, INSA Lyon, Université Claude Bernard Lyon 1, CPE Lyon, INL, UMR 5270, 69130 Écully, France

[3] School of Engineering, RMIT University, Melbourne 3001, Victoria, Australia

Article history

Received September 21, 2022
Received in revised form September 24, 2022
Accepted September 24, 2022
Available online September 30, 2022

Abstract

In this paper, light extraction from remote phosphor LEDs were calculated in Zemax OpticStudio. The dependence of the optical characteristics of the remote phosphor LED on the parameters of phosphor and its geometrical form was considered. In case of a thin plate as a remote phosphor, phosphor particle size, phosphor mass fraction and phosphor plate thickness were carefully analyzed. Furthermore, a plane-convex lens and Fresnel lens were also considered as geometrical form of remote phosphor. The simulation results show that color coordinates of LED, using remote phosphor plate (thickness 0.25 mm, mass fraction 30% and particle size 3 μm of phosphor), are the closest to D65 point on color space compared to other considered LEDs. The use of plane-convex lens (thickness 1 mm, radius of curvature 7 mm, base diameter 7 mm) as remote phosphor results in the maximum luminous flux compared to other forms.

Keywords: Light emitting diodes; Remote phosphor; Numerical modeling; Color coordinates

1. INTRODUCTION

Light emitting diodes (LEDs) have established themselves as modern technology, which is capable of providing high luminous efficiency and good color rendering. One of the most promising methods for manufacturing a white LED is the combination of a blue LED chip with a phosphor coating.

The method of applying the phosphor coating largely determines many characteristics of LEDs, including the luminous efficiency, angular color uniformity and color coordinates. One of them is mixing the phosphor powders with a polymer compound and applying this composition directly to the LED chip, which is known as conventional dispensing phosphor coating. However, in this case, a considerable portion of light is absorbed in the components of the LED package, because the phosphor layer is close to the LED chips and substrate [1]. Another drawback of this configuration is the heating of the phosphor particles due to contact with the LED chip, which heats up during operation [2].

The configuration with the remote phosphor provides a lower amount of light trapped in LED chips and, as a result, the efficiency of the LED device is significantly increased. Furthermore, this configuration can lower the temperature of the phosphor layer, because the LED chip does not have direct contact with the phosphor layer.

The most common white LEDs using phosphor is combining blue LED made of gallium nitride (GaN) and yttrium-aluminum garnet phosphor doped with trivalent cerium (YAG, YAG:Ce) [3]. Characteristics of phosphor play an important role in determining the final optical performance of LED devices. Many studies investigated the impact of phosphor properties on LED performance [4–6].

* Corresponding author: S. N. Lipnitskaya, e-mail: snlipnitskaya@itmo.ru

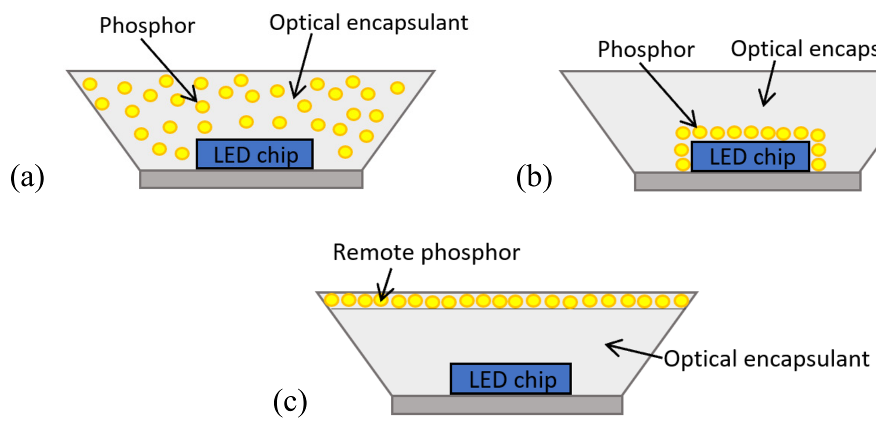

Fig. 1. Schematic of white LEDs with (a) the dispense phosphor coating (phosphor-in-cup), (b) the conformal phosphor coating, and (c) remote phosphor layer

The physical location of phosphor drastically influences the work of LED — the propagation path and light energy is affected by scattering and absorption by the phosphor — therefore it is a primary consideration for device packaging. In Ref. [7] the phosphor powders are mixed with the optical encapsulant and uniformly dispersed in a cup reflector with a mounted LED chip. Therefore, phosphor powders are located in the vicinity of the chips. One of the drawbacks of this approach is that it is difficult to precisely control the thickness and shape of the coating layer resulting in an inhomogeneous distribution of phosphor and poor angular color uniformity, which often causes "yellow ring." However, in this case, it is necessary to take into account the absorption of phosphor radiation by LED chips and the heating of the phosphor coating due to direct contact with the chips.

In order to overcome the disadvantages of the dispense phosphor coating (Fig. 1a) the conformal phosphor coating (Fig. 1b) had been proposed [8]. The conformal coating method provides a phosphor layer with uniform thickness and the same shape of a LED chip surface to obtain high angular color uniformity.

Nevertheless, in the case of phosphor-in-cup (dispense phosphor coating) and conformal coating phosphor configurations powders are applied directly on top of the LED chip, while conformal method is even more proximate. Addressed issue cause drastic complications. First of all, the heat from the operating LED chip, caused by reflected light from phosphor, will increase the working temperature of the phosphor material and seriously decrease their emission efficiency. Secondly, it has been confirmed that nearly 50–60% of the light re-emitted by the phosphor backscatters to the LED chip, resulting in low luminous efficiency [9–10].

The lumen output and the conversion efficiency of a phosphor coated white LED device with in-cup phosphor and remote phosphor geometries with their dependency on the size of YAG:Ce particles were studied in Ref. [11]. It was highlighted that under the same conditions such as correlated color temperature and phosphor size, lumen output of the remote phosphor package is less sensitive to phosphor size and higher than that of the in-cup phosphor package.

This work studies LEDs with remote phosphor layer (Fig. 1c). In order to achieve high performance of white LEDs, effects of phosphor particle size, concentration, thickness and the form of remote phosphor on the optical performance of white LEDs are carefully considered.

2. RESEARCH METHOD

In this work numerical modeling was used. Models of remote phosphor LEDs were calculated in Zemax OpticStudio. This program uses ray tracing according to the Monte Carlo method. Verification of the remote phosphor LED models was carried out by comparing the simulation results with the experimental results given in the literature [1].

In order to optimize the optical properties of remote phosphor LED, thickness of remote phosphor plate, concentration and phosphor particle size are in need to be adjusted. Thickness of remote phosphor, concentration and particle size were varied. Depending on the thickness of phosphor plate, the concentration of phosphor particles was calculated and set in such way that phosphor mass fraction on the volume of the phosphor plate was the same for every thickness.

The model of a remote phosphor LED with phosphor plate is demonstrated in Fig. 2. A LED chip was modeled

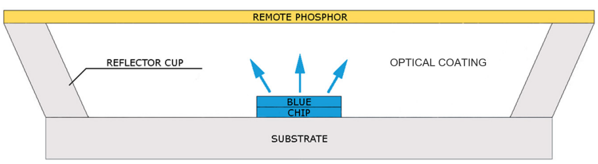

Fig. 2. Model of a remote phosphor LED with phosphor plate.

in Zemax OpticStudio as a parallelepiped with dimensions of 1/1/0.25 mm and material properties of GaN. A light source area with dimensions of 0.5/0.5 mm is located inside the modeled parallelepiped. The distribution of the radiation intensity over the entire surface of the emitting area corresponds to the Lambert law. Emission wavelength of the chip is 445 nm. The source has a power of 0.2 watts. Number of rays for tracing was set to $8 \cdot 10^6$.

The chip is mounted on a cylindrical metal substrate with a thickness of 0.5 mm and a radius of 3 mm. The light scattering on the surface of the substrate was specified by the ABg model of surface scattering (model parameters: A = 0.057, B = 0.005, g = 2), the absorption is 5%, which corresponds to the ceramic substrates used in the production.

The reflector cup of an LED has a base radius of 3 mm. The radius and height of the upper surface is 3.5 mm and 1.2 mm, respectively. The reflector cup is filled with the optical coating. A refractive index of the optical coating corresponds to the silicone encapsulant (1.5257 for wavelength 445 nm and 1.5176 for 570 nm). The inner surface of the reflector cup mirrors 95% and absorbs 5% of the incident radiation.

Remote phosphor was modeled as an optical element with phosphor particles, which is placed on top of the optical coating. The refractive index of the phosphor particles was set to 1.8504 for a wavelength of 445 nm, which corresponds to the refractive index of a phosphor based on yttrium aluminum garnet. The peak luminescence wavelength of the phosphor is 570 nm.

This work studies geometries of remote phosphor: phosphor plate, plane-convex lens and Fresnel lens. A plane-convex lens has a thickness of 1 mm, radius of curvature 7 mm and base diameter 7 mm. To specify the Fresnel lens, it is necessary to indicate the thickness 0.2 mm, radius of curvature $R_c = 7$ mm and base diameter 7 mm. The number of concentric rings per 1 mm (frequency, N) was set as 6 mm^{-1}. The parameters of the aspherical surface are given by the formula

$$z = \frac{R_c r^2}{1 + \sqrt{1 - R_c^2 r^2}}, \tag{1}$$

where z is the curvature radius of the surface.

In this work, phosphor particle radius will be defined as phosphor particles size. The phosphor plate thickness h was selected 0.05 mm, 0.1 mm, 0.15 mm, 0.2 mm, and 0.25 mm. The phosphor particle radius r was selected 3 μm, 5 μm, 6.5 μm, 8 μm, and 10 μm. To maintain the mass fraction of phosphor W (15%, 30%, 50% or 75%) for each phosphor particle size it is necessary to change the concentration of phosphor particles.

The mass fraction of phosphor within a plate is the ratio of the mass of that phosphor m_{phosphor} to the total mass of the mixture, which is the mass of the phosphor m_{phosphor} plus the mass of the silicone m_{silicone}. The following formulas were used for calculation of phosphor mass fraction:

$$W = \frac{m_{\text{phosphor}}}{m_{\text{phosphor}} + m_{\text{silicone}}} \times 100\%, \tag{2}$$

$$m_{\text{phosphor}} = V_{\text{phosphor}} \times \rho_{\text{phosphor}}, \tag{3}$$

$$m_{\text{silicone}} = (V_{\text{plate}} - V_{\text{phosphor}}) \times \rho_{\text{silicone}}, \tag{4}$$

where ρ_{phosphor} is the density of YAG:Ce, which is 4.55 g/cm^3; ρ_{silicone} is the density of silicone encapsulant, which is 1.5 g/cm^3, $V_{\text{phosphor}} = 4\pi r^3 c V_{\text{plate}}$ is the volume of phosphor. Here r is the mean radius of a phosphor particle, c is the phosphor concentration, and volume of a plate $V_{\text{plate}} = \pi R^2 h$, where R is the radius of the phosphor plate and h is the thickness of the plate.

3. RESULTS AND DISCUSSION

The line graph in Fig. 3 illustrates the change in luminous flux in regard to remote phosphor plate thickness at four different mass fractions with different sizes of phosphor particle.

The numbers, that are pointed in the graphs for the given phosphor thickness and number of particles, are associated with the numbers on color distributions. The points, that are circled, are the cases, when the matching characteristics of phosphor on graphs are able to obtain white light.

The highest luminous flux is provided by phosphor thickness $h = 0.25$ mm and mass fraction 75%, while the minimum luminous flux is seen with h = 0.05 mm and $W = 15\%$. White light can be seen to be obtained (the circled point) with phosphor thickness 0.25 mm and mass fraction 75%.

Summarizing all graphs above, the increase of plate thickness (while maintaining their mass fraction constant) results in the increase of luminous flux of remote phosphor LED. It can be due to an increase in the number of particles and, as a consequence, an increase in collisions of blue rays from LED chip with phosphor particles and their conversion to yellow. Discussed effect makes a greater contribution to the luminous flux, since the sensitivity of the eye at a wavelength of 570 nm is higher than at a wavelength of 460 nm.

Fig. 4 shows that with the increase of phosphor size particle, the decrease in luminous flux of remote phosphor LED with all presented phosphor thickness can be observed. The highest luminous flux is observed with radius of phosphor particle 3 μm and plate thickness of 0.25 mm, while the minimum luminous flux is seen with phosphor particle size 10 μm and phosphor thickness of 0.05 mm.

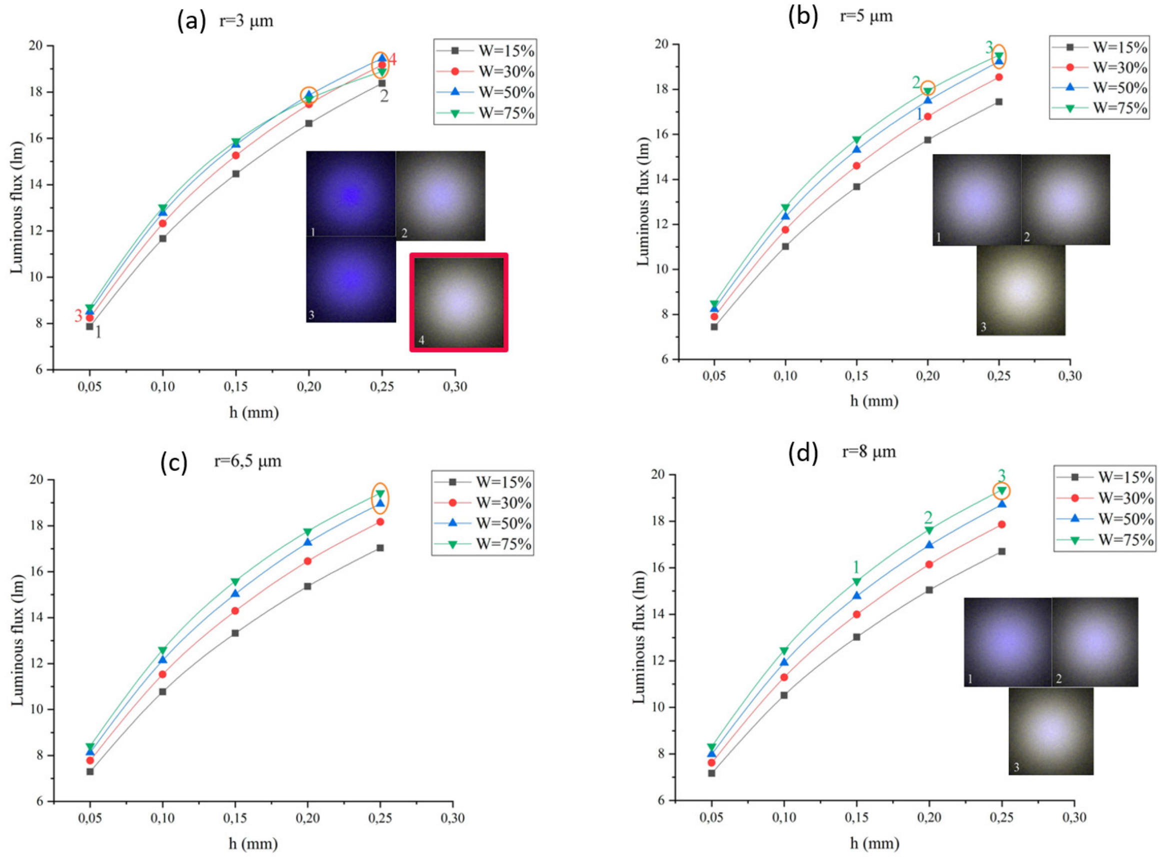

Fig. 3. Luminous flux for different phosphor plate thickness at four mass fractions with different sizes of phosphor particle: (a) $r = 3$ μm, (b) $r = 5$ μm, (c) $r = 6.5$ μm, (d) $r = 8$ μm.

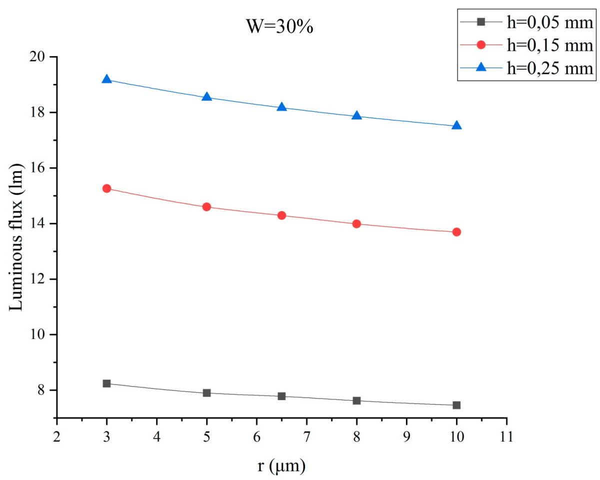

Fig. 4. Luminous flux for different radius of phosphor particles at three phosphor plate thickness with mass fraction of 30%.

Overall, the following conclusions can be made about the dependence of phosphor particle size. The growth of phosphor particle size leads to the decrease in luminous flux of a LED. It is possible that an increase in particle size leads to a decrease in probability of a blue emission from a chip encountering phosphor particles. Providing that, it is likely that the low probability of encountering phosphor particles results in increase in light scattering towards the substrate, LED chip and reflector cup.

Over the course of investigation on influence of phosphor plate parameters, it has been seen that phosphor plate thickness, phosphor mass fraction and phosphor particle size play a great role in luminous flux of remote phosphor LED. Therefore, it is prudent to investigate the change of color of LED light on the color space.

In order to optimize the form of remote phosphor, three different geometries of remote phosphor were investigated — phosphor plate, plane-convex lens and Fresnel lens. Optimizing the form of the remote phosphor LED was based on investigating the change of luminous flux, color coordinates and color distribution, and based on these optical parameters of a LED, choosing the best form for remote phosphor. Best result corresponds to a case, when white light is obtained, with a good luminous flux, color coordinates around white point and uniformity of white light on color distribution.

The results of calculations (Fig. 5) can be summarized into several conclusions. The behavior of luminous flux of remote phosphor LED for all examined phosphor geometries are almost the same. Comparing all remote phosphor forms, plane-convex lens provides the maximum value of

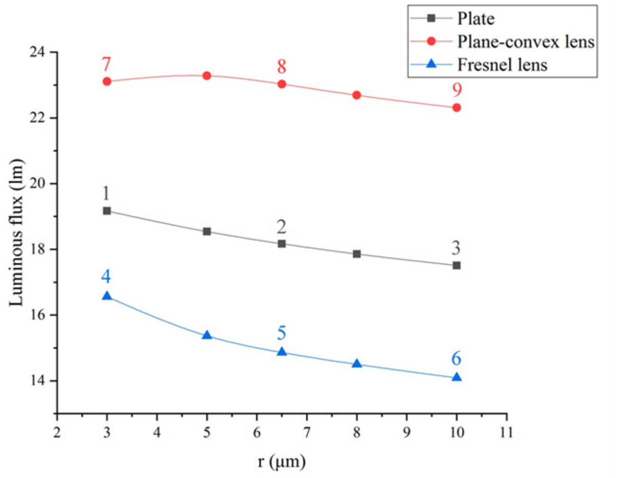

Fig. 5. Dependence of luminous flux for three forms of remote phosphor on phosphor particle size.

luminous flux. At the same time, using Fresnel lens results in a low luminous flux. In every case, the maximum value of luminous power is a result of phosphor particle with the size 3 μm.

In more detail, using a thin plate as a remote phosphor leads to a stable increase of luminous flux with the growth of phosphor particles size. Therefore, it can be said that $r = 3$ μm is the value of mean particle size, which produces the maximum value of luminous flux.

Analyzing Fresnel lens as a remote phosphor, it can be concluded that with the increase of particles size the behavior of luminous flux is almost the same as for phosphor plate. However, to bring into a comparison to a phosphor plate, values of luminous flux of Fresnel lens, throughout the increase of particle size, are below values of a plate. In this case, the maximum value of luminous flux is achieved with 3 μm particles size and minimum value with 10 μm.

For the configuration, when a plane-convex lens is used, the behavior of luminous flux is different. With the increase of mean radius of the phosphor particles, the luminous flux of the LED device is almost constant. In this case, the maximum value of the luminous flux is observed at a particle size of 5 μm and the minimum value at 10 μm.

The form of remote phosphor and the growth of phosphor particle size leads to the change in colorimetric characteristics of remote phosphor LED (Fig. 6). The numbers on color space CIE 1931 correspond to the numbers on Fig. 5. Furthermore, color distributions of listed cases were also investigated.

From Fig. 6 it can be said that the size of phosphor particles and the geometry of remote phosphor greatly affect the color coordinated of emitted light. Coordinates of a phosphor plate (1–3) and Fresnel lens (4–6), with the growth of phosphor particle size, move to the blue region on the color space. Simultaneously, color coordinates of LED with plane-convex lens (7–9) as remote phosphor for all phosphor sizes are in the yellow region. However, the increase in particle size leads closer to the white point D65 on color space.

The closest to the white point D65 is point 1, which corresponds to a phosphor plate with phosphor particle size 3 μm. Point 4, which matches Fresnel lens and phosphor particle size 3 μm, is the second closest to the white point.

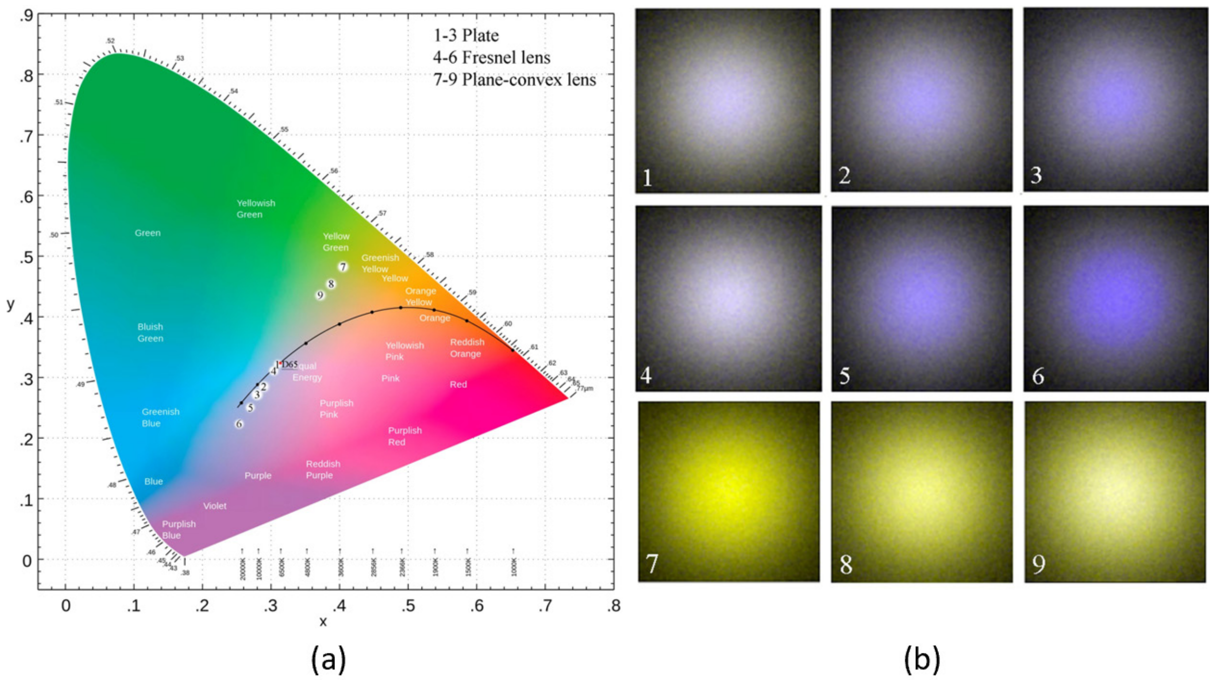

Fig. 6. The CIE 1931 color space with color coordinates for different forms of remote phosphor (a); color distribution (b).

4. CONCLUSION

In case of a thin plate as a remote phosphor, phosphor particle size and phosphor plate thickness with phosphor mass fraction 15%, 30%, 50% and 75% were carefully analyzed. Color coordinates of LED, using remote phosphor plate with thickness 0.25 mm, mass fraction 30% and phosphor particle size 3 µm, are the closest to D65 point on color space compared to other remote phosphor forms. The use of Fresnel lens as remote phosphor results in the minimum luminous flux compared to other forms. For Fresnel lens the increase of phosphor particle size (while maintaining their mass fraction constant) results in the decrease of luminous flux and color coordinates of remote phosphor LED moving to the blue region in color space. The use of plane-convex lens as remote phosphor results in the maximum luminous flux compared to other forms. For plane-convex lens the increase of phosphor particle size (while maintaining their mass fraction constant) results in small decrease in luminous flux and color coordinates of remote phosphor LED being in a yellow region in color space.

REFERENCES

[1] S.N. Lipnitskaya, K.D. Mynbaev, V.E. Bougrov, A.R. Kovsh, M.A. Odnoblyudov, A.E. Romanov, *Effects of light scattering in optical coatings on energy losses in LED devices*, Tech. Phys. Lett., 2013, vol. 39, no. 12, pp. 1074–1077.

[2] V. Pilla, T. Catunda, S.M. Lima, A.N. Medina, M.L. Baesso, H.P. Jenssen, A. Cassanho, *Thermal quenching of the fluorescence quantum efficiency in colquiriite crystals measured by thermal lens spectrometry*, J. Opt. Soc. Am. B., 2004, vol. 21, no. 10, pp. 1784–1791.

[3] A.A. Setlur, J.J. Shiang, M.E. Hannah, U. Happek, *Phosphor quenching in LED packages: measurements, mechanisms, and paths forward*, Proc. SPIE, 2009, vol. 7422, art. no. 74220E.

[4] R. Hu, X. Luo, S. Liu, *Effect of the amount of phosphor silicone gel on optical property of white light-emitting diodes packaging*, in: 2011 12th International Conference on Electronic Packaging Technology and High Density Packaging, IEEE, 2011, pp. 1–4.

[5] C. Sommer, F. Reil, J.R. Krenn, P. Hartmann, P. Pachler, H. Hoschopf, F.P. Wenzl, *The impact of light scattering on the radiant flux of phosphor-converted high power white light-emitting diodes*, J. Light. Technol., 2011, vol. 29, no. 15, pp. 2285–2291.

[6] C. Sommer, F.P. Wenzl, F. Reil, J.R. Krenn, P. Pachler, S. Tasch, P. Hartmann, *A comprehensive study on the parameters effecting color conversion in phosphor converted white light emitting diodes*, Proc. SPIE, 2010, vol. 7784, art. no. 77840D.

[7] A. Keppens, Y. Zong, Y. Ohno, G. Deconinck, P. Hanselaer, *Determining phosphors' effective quantum efficiency for remote phosphor type LED modules*, Proc. CIE Tutorial and Expert Symposium on Spectral and Imaging Methods for Photometry and Radiometry, CIE, 2010, pp. 39–42.

[8] V.K. Khanna, *Fundamentals of solid-state lighting: LEDs, OLEDs, and their applications in illumination and displays*, CRC Press, Boca Raton, 2014, 604 p.

[9] K. Yamada, Y. Imai, K. Ishii, *Optical simulation of light source devices composed of blue LEDs and YAG phosphor*, J. Light Vis. Environ., 2003, vol. 27, no. 2, pp. 70–74.

[10] Y. Zhu, N. Narendran, Y. Gu, *Investigation of the optical properties of YAG: Ce phosphor*, Proc. SPIE, 2006, vol. 6337, art. no. 63370S.

[11] N.T. Tran, J.P. You, F.G. Shi, *Effect of phosphor particle size on luminous efficacy of phosphor-converted white LED*, J. Light. Technol., 2009, vol. 27, no. 22, pp. 5145–5150.

УДК 535.2:535.6+628.9

Численное моделирование вывода света из светодиодов с удаленным люминофором

С. Н. Липницкая[1], Ю. Ю. Дудко[2,3], И. Г. Смирнова[1]

[1] Лаборатория однофотонных детекторов и генераторов, Университет ИТМО, Кронверкский пр., 49, лит. А, Санкт-Петербург, 197101, Россия
[2] École Centrale de Lyon, CNRS, INSA Lyon, Université Claude Bernard Lyon 1, CPE Lyon, INL, UMR 5270, 69130 Écully, France
[3] School of Engineering, RMIT University, Melbourne 3001, Victoria, Australia

Аннотация. В статье представлены результаты расчета вывода света из светодиода с удаленным люминофором в Zemax OpticStudio. Рассмотрена зависимость оптических характеристик светодиода от параметров удаленного люминофора и его геометрической формы. В случае удаленного люминофора, имеющего форму тонкой пластины, был проведен анализ для разного размера частиц люминофора, массовой доли люминофора и толщины пластины. Так же был рассмотрен удаленный люминофор в форме плосковыпуклой линзы и линзы Френеля. Расчеты показали, что координаты цветности светодиода с использованием удаленного люминофора в форме тонкой пластины (толщина 0,25 мм, массовой долей 30% и размер частиц люминофора 3 мкм) наиболее близки к координатам цветности стандартного источника D65 в цветовом пространстве, чем координаты других рассмотренных светодиодов. Использование плосковыпуклой линзы (толщина 1 мм, радиус кривизны 7 мм, диаметр основания 7 мм) в качестве удаленного люминофора приводит к максимальному световому потоку по сравнению с другими рассмотренными формами удаленного люминофора.

Ключевые слова: светодиод; удаленный люминофор; численное моделирование; координаты цветности