Analysis of Factors Affecting Color Distribution of White LEDs

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Abstract

The color uniformity is a critical index in the evaluation of high quality white light emitting diodes (LEDs). The main factor affecting the color distribution is the state of the phosphor. The secondary factor is the optical structure. This paper analyzes two parameters of the phosphor layer (thickness and concentration) and six optical structures. Results indicate that the structures with reflector have lower color uniformity. The hemispherical shape of phosphor layer could improve the performance of color distribution and make the variation smaller. Between the two parameters of phosphor, the concentration has the greatest impact on the color uniformity, the second one is the thickness. Through the analysis, it is suggested that the thickness and concentration should be precisely controlled. Otherwise, the color uniformity will be varied significant and may generate serious yellow rings.

Introduction

Light emitting diodes has made remarkable progress on the past four decades with the rapid development of compound semiconductor technology. Since the first red LEDs that was invented by Holonyak and Bevacqua in 1962[1], great efforts have been put into study to obtain brighter LEDs. In early 1990s, Nakamura successfully grew the blue and green LEDs on GaN substrate, which has a profound impact on the progress of LED technology[2, 3]. Nowadays there are three basic methods to obtain white LEDs, one is the monochromatic RGB LEDs, another is phosphor converted LEDs (PC LEDs), the third is based on UV LEDs. The most commercially available white LEDs is dichromatic PC LEDs[4], which generates the white light by mixing the blue light from LED chip with the broadband yellow light excited by phosphor[5, 6]. Since the white light LEDs has superior characteristics such as high efficiency, small size, long life, dependable, low power consumption, high reliability and mechanically rugged[7], therefore, a new concept of illumination named solid state lighting (SSL) in terms of high power LEDs is proposed[8]. With the accelerated advancement of LED technology, the input electrical power of LEDs was jumped to 1W or more by increasing the chip size from 350 microns to 1mm. The luminous efficiency of high power LEDs was also increased from 25 lm/W in 1999 to more than 100 lm/W in 2007 for a driving current of 350mA[9]. Consequently, the market for high power LEDs is growing rapidly in various applications such as large size flat panel backlighting, street lighting, vehicle forward lamp, museum illumination and residential illumination[10, 11]. It has been widely accepted that SSL will be the fourth illumination source to substitute incandescent lamp, fluorescent lamp and HID lamp[12]. The broad application prospect of SSL has attracted great attention on the study of LEDs[13].

The main function of LED packaging is to protect the LED chip, enhance the light extraction and provide a path for dissipating the generated heat. The packaging is the critical bridge between the LED chips and applications for end-users. Now the LED packaging technology has been improved much to make full of the potentials of rapidly developing high power LED chips[14, 15]. Products of corporations such as the Lumileds's Luxeon K2 series, the Cree's XLamp series, the Osram's Golden Dragon series, offer high performance LED modules in terms of various packaging structures, in which the phosphor is dispersed on the surface of chip. To improve the packaging performance such as the light extraction efficiency, researcher have made remarkable efforts and achieved many valuable results[16, 17, 18, 19], for example, the scattered photon extraction method (SPE) [20, 21], the silicone based packaging platform [22], wafer level packaging [23], *et al*..

High luminous efficacy, in general, is the main purpose of optical design to improve light extraction, but the color uniformity should not be neglected in the efforts to obtain high quality white light LEDs. It is another key evaluation index like the correlated color temperature and color rendering index, but nowadays there doesn't attach enough importance on the color distribution. Non-optimized or un-suitable structure and process could induce unexpected phenomenon such as the yellow ring. We found this situation in many corporations' packaging modules as shown in Figure 1. This color ununiformity (adj not a noun!) will influence the real performance of illumination, thus leading to discomfort for the eye's vision.

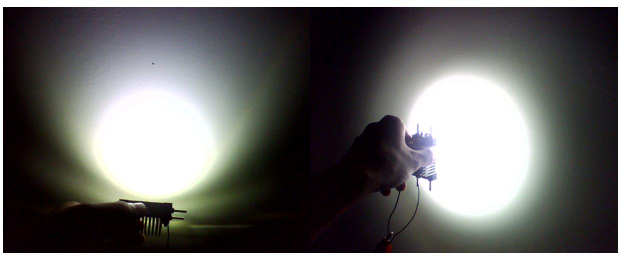

Figure 1. The yellow ring in some LED modules.

Fundamentally, the main factor affecting the color distribution is the state of the phosphor. The secondary factor is the structure that could change the light propagation and

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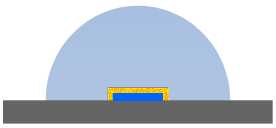
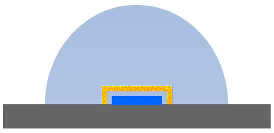
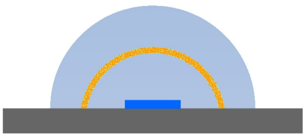
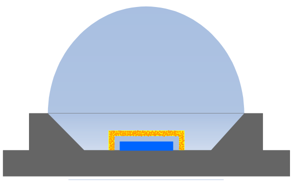
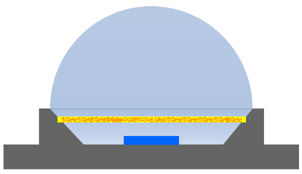
intensity distribution in the space. There are energy conversion and re-emission, scattering and absorption in the phosphor layer. Both the blue light and converted yellow light must be sufficiently scattered by the phosphor particles to generate uniform white light. Different optical structures with various states of phosphors in terms of location, thickness, concentration, shape, etc. will greatly influence the performance of LEDs, especially the color uniformity. Lumileds proposed a new phosphor coating technology named conformal coating, which dispersed a uniform phosphor film on the surface of the chip. This can improve that the variation of the CCT drops to ~80K[24].

validated and the total ray trace number was finally 800000 to obtain converged results.

Problem Statement

The LED module generally consists of the heat slug, chip, phosphor, silicone packages and lens. Reflector is also necessary for some modules, for example, the Golden Dragon of Osrams. It is well known that the performance of LED module greatly depends on the technology of chip, but the packaging elements are also critical in the process of trying to achieve high quality white light LEDs. In the optical design for the packaging, the primary considerations are the phosphor, lens and reflector.

Table 1. The optical structures and variable parameters for the numerical simulation.

I		Location (mm)	0	0
		Thickness (mm)	**0.04~0.2**	0.1
		Concentration (mm^{-1})	19.85	**9.92~49.5**
II		Location (mm)	0.05	0.05
		Thickness (mm)	**0.04~0.2**	0.1
		Concentration (mm^{-1})	19.85	**9.92~49.5**
III		Location (mm)	2	2
		Thickness (mm)	**0.04~0.2**	0.1
		Concentration (mm^{-1})	19.85	**9.92~49.5**
IV		Location (mm)	0.05	0.05
		Thickness (mm)	**0.04~0.2**	0.1
		Concentration (mm^{-1})	19.85	**9.92~49.5**
V		Location (mm)	1.9	1.9
		Thickness (mm)	**0.04~0.2**	0.1
		Concentration (mm^{-1})	19.85	**9.92~49.5**

To further investigate the focused issues in the efforts of trying to obtain high color uniformity for white light LEDs, this paper discusses various parameters of phosphor layer on the performance of LEDs. The parameters include the thickness, concentration. In addition to prove that the results are reliable and implantable for packaging production, six different optical structures are studied. A non-sequential ray trace method was applied, which was based on the Monte-Carlo theory. The power ratio of yellow light to blue light, which is named yellow blue ratio, is used to illustrate the correlated color temperature (CCT). The curve of color distribution was fitted by non-linear least square method. The uniformity of color distribution is the ratio of the max value to the min value in the range of ±65° of the emitted angle, in which the light intensity is considered effective for the design of illumination lamps. The parameters of the models were

The phosphor layer is the mixture of phosphor particles and silicone. It absorbs blue light and re-emits yellow light. When alternating the thickness and concentration of the phosphor layer, there will be different optical behaviors for blue light and converted yellow light. The variations of these behaviors will affect the initial energy of extracted blue light and yellow light.

The lens and reflector are normally used to enhance the light extraction and change the light distribution by the refraction of materials and reflection on the interface. They could affect the final energy of extracted blue light and yellow light. Now the commonly used packaging materials

However, there still are not enough studies on these elements to better understand the design guidelines for nowadays used packaging structures. As the basic steps to realize these factors, the numerical simulation and analysis are focused on the issues about the relationship between the color uniformity and the characteristics of phosphor layer and the packaging structure. The effects of phosphor layer are the primary considerations in this paper. Obviously it is difficult to explain the influencing mechanism only by these simple models, but this investigation could make clear of what the optical design should avoid. Therefore, the objectives of this paper are 1)To simulate different structures with various states of phosphor layer; 2) To explain the simulation results and trying to find the principles about these factors; and 3)To provide some suggestions for the optimized optical design.

Numerical Model and Simulation

This paper mainly concerns six different optical structures that are depicted in Table 1. For each structure, the thickness and concentration of phosphor are changed to investigate the effects of variation. To evaluate the impact of the reflector on the color uniformity, three numerical models in terms of type IV, V and VI have the reflector to compare the front three non-reflector models of type I, II and III. The base and top diameter of the reflector cup is 3 mm and 8mm, and the height is 2 mm. The optical parameters of the surface on the board and reflector are assumed to have 85% perfect reflection, 5% scattering and 10% absorption. The radius of the lens for all types is large enough to 4 mm to minimize the effects of lens's size on the light propagation. Since this paper mainly discusses the effects of phosphor, the dimensions of the reflector and the lens are assumed to be the same.

In the first model, the phosphor is directly coated on the chip. The variable parameters are the thickness and concentration. In the second and fourth structures, the chip is firstly packaged with a thin silicone film, and then coated with the phosphor layer. Both types increase the thickness of the silicone film to change the distance between the phosphor layer and the chip. When the variable parameters are the thickness and concentration, the distance is kept to be 0.05mm. In the third structure, the phosphor layer is a hemispherical film with increasing the radius to change the location. The fourth structure firstly disperses the silicone in the reflector, and then disperses the phosphor silicone uniformly to make a thin phosphor film. Through increasing the volume of the inner silicone, the height of the film could be changed from 0.2 mm to 1.9 mm. The sixth structure only discusses the effects of location, which increases the radius of the spherical phosphor layer. For all types, when one of the three variable parameters is changed, the another two parameters are kept un-changed. For example, when the location is changed, the thickness and concentration are 0.1 mm and 19.85 mm^{-1} in these models. This paper applies the sum of the absorption and scattering coefficient to represent the concentration. This will be explained in the following discussions.

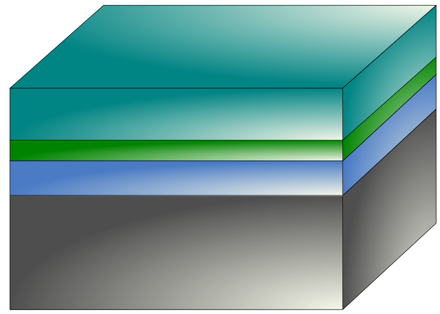


Figure 2. The LED chip model for the numerical simulation.

The LED chip model is depicted in Figure 2, which is a simplified 1mm×1mm Cree LED chip. The top surface of the Si is coated with Au to reflect the back light. We considered that the light emits uniformly from the MQW layer, since the direction of the photons that are excited by the combination of the electrons and holes in the MQW layer is arbitrary. Considering that the area of the top and down surface is much larger than that of the side surface, the model defines the two surfaces as the light sources by ignoring the side emitting lights. The optical properties are illustrated in Table 2[25].

Table 2. Optical properties of the LED chip.

	N-GaN	MQW	P-GaN
Refractive Index	2.42	2.54	2.45
Absorption Coefficient (mm^{-1})	8	8	8

The definition of the optical properties for the phosphor layer is very important, since it relates to the correction and precision of the simulation results. When one beam of blue light passes through one phosphor particle, the phenomenon such as the transmission, refraction, scattering and absorption will occur simultaneously, and thus affects the light propagation and weakens the blue light energy. The absorbed blue light will re-emit broad-band yellow light, which should be affected by other phosphor particles. The average radius of phosphor particle is 5~8 microns as shown in Figure 3, and generally the number of particles is 10000~100000 per mm^3 in the phosphor silicone. Since there may be millions of phosphor particles in the phosphor layer, the light will encounter many particles in the propagation path and thus be scattered many times before it transmits through the phosphor layer. During the multi-scattering process, the blue light energy will be weakened gradually by absorption, but the converted yellow light energy will be increased for each scattering. The scattering will also influence the intensity distribution of the light rays. It's well known that the white light is generated by the combination of the yellow light and blue light. If the power ratio of the yellow light to the blue light is too high or too low in partial zones of the space, the color of the light will tend to become yellow or cool white. This is the main reason affecting the color uniformity.

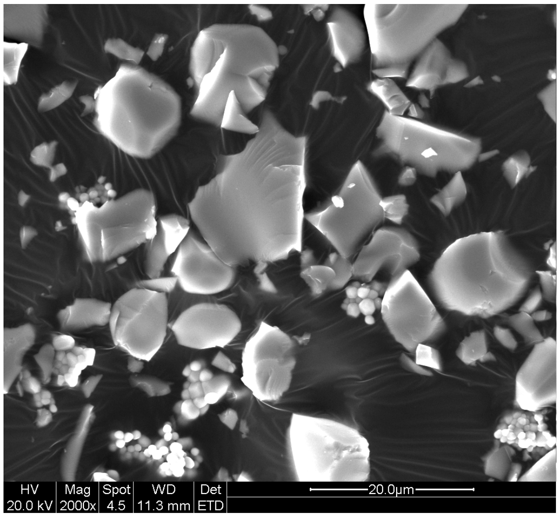


Figure 3. SEM picture of the phosphor particles.

Since the optical behavior of the light in the phosphor layer is so complicated, the simplification of the optical properties for the phosphor is necessary to make the simulation practicable. Considering the phosphor layer as a bulk scattering material, it is an easy and effective method that applies the scattering and absorption coefficient to represent the totally effects of the phosphor particles on the light propagation [26, 27, 28, 29]. Therefore, when a beam of rays passes through the phosphor layer, the transmitted light energy can be expressed by Equation 1.

$$I(x) = I_0 e^{-(\mu_\alpha + \mu_s)x} \quad (1)$$

where I_0 is the initial power of the light and $I(x)$ is the residual power; μ_α and μ_s are the absorption coefficient and scattering coefficient of the phosphor; and x is the thickness of the phosphor layer. Because the variations of the concentration could influence μ_α and μ_s, this paper applies the sum of μ_α and μ_s to represent the concentration. High concentration indicates that the sum is bigger.

The scattering distribution function of the phosphor layer, which is used to generate the random direction of the scattered light, is based on the Henyey-Greenstein model. It is indicated in equation 2.

$$p(\theta) = \frac{1-g^2}{4\pi(1+g^2-2g\cos\theta)^{3/2}} \quad (2)$$

where g is called the anisotropy factor. In the phosphor layer, since the scattering of the light by the particles is isotropy, g is zero.

Since there are two parameters for the phosphor layer, the definition for the optical properties should be specific for each case. When the thickness is changed, the concentration of the phosphor is unchanged in the first case. Therefore, the optical parameters keeps the same. This paper assumes that the absorption and scattering coefficient is 8 mm-1 and 11.85 mm-1 for blue light. However, it is considered to be transparent when the incident ray is yellow light. Therefore, the absorption coefficient is set as 0 mm^{-1}. Because of the non-absorption, the yellow light will be scattered more times than the blue light, which induces that the yellow light should be exhausted later by the phosphor particles in the propagation process. Therefore, the scattering coefficient is 16.25 mm^{-1} for yellow light.

For the second case, since the concentration is changed, the variation of the optical parameters is listed in Table 3.

Table 3. Optical parameters of phosphor in the second case.

	Absorption Coefficient (mm^{-1})		Scattering Coefficient (mm^{-1})	
	Blue light	Yellow Light	Blue Light	Yellow Light
1	20	0	29.5	40.45
2	13.3	0	19.8	26.95
3	10	0	14.8	20.33
4	8	0	11.85	16.25
5	6.65	0	9.88	13.48
6	5.72	0	8.465	11.62
7	5	0	7.4	10.173
8	4.44	0	6.57	8.99
9	4	0	5.92	8.09

Since the transmittance of the silicone materials is over 95% for visible light, it is generally considered that the silicone materials are transparent to visible light. Therefore, the absorption coefficient is 0 mm^{-1} in the numerical simulation. The refractive index of silicone is 1.5, which can be bought in corporations such as DowCornig.

Based on the above settings, the simulation steps of the numerical model are:

1) Defining the material properties of each layer;
2) Defining the top and down surface of the MQW layer as the light source, and then inputting the light power;
3) Ray tracing and collecting the simulation data;
4) Re-defining the material properties of each layer;
5) Re-defining the top and down surface of the phosphor layer as the light source, the power of which is calculated from the absorbed blue light; and the conversion efficiency of the phosphor is 80%;
6) Ray tracing and collecting the simulation data; and
7) Calculating the simulation results of each case.

In this simulation procedure, the blue light output and yellow light output are computed separately to easily investigate the impaction of the phosphor's states on the color temperature. The yellow blue ratio, which is the value of the yellow light power divided by the blue light power, is used to represent the correlated color temperature.

Therefore, the color distribution of the LEDs is the variation of the yellow blue ratio in the space. High yellow blue ratio means that the CCT is lower and the light tends to be warm white. Oppositely, low yellow blue ratio means the CCT is higher and the light tends to be cool white.

The color uniformity is the ratio of the maximum value to the minimum value in the effective angels. In the following discussions, to calculate the color uniformity, this paper only analyzes the data in the range of ±65° of the emitted angle. This is due to the fact that most of the light energy is in this range, and the intensity of the side angle is obviously small and may be undetectable by eyes.

Simulation Results and Discussions

The simulation results are shown in the following figures. Each figure contains the color distribution curve, the color uniformity and the illustration for the specific case.

The effects of phosphor's thickness on the color distribution are depicted in Figures 4-8. It can be found that the yellow blue ratio curve is ascended when the thickness is increased. That means the color tends to be warm white or yellow light. The rising tendency of the side angles are more significant than that of central angles, especially in the first, second and fourth structures. That means there are fewer flat zones but more fluctuant zones in the cure. Therefore, the color uniformity in those cases is reduced gradually and the phenomenon of yellow ring is more serious. Although we could find the same variation of the curve in the third and fifth structures from 0° to 180°, the variation in the range of ±65° is not so significant. The color uniformity is even slightly increased.

The reflector also has great impact on the color uniformity when the thickness is changed. For example, the color uniformity in the second structure is around 0.5~0.6, but in the fourth structure it is aroud 0.3~0.4. The maximum value points in the curves are also obvious higher than those without reflector.

The remote phosphor location could make the variation of color uniformity smaller. In the third and fifth structure, the color uniformities are even increased slightly.

It is a better choice to utilize the thinner phosphor layer to improve the color uniformity, but attention is paid to the color trends of the LEDs. Because the concentration is not changed, the thinner phosphor layer in all cases has high CCT or even blue color in some zones. Therefore, in the progress to achieve high color uniformity LEDs, the thickness is not the unique approach.

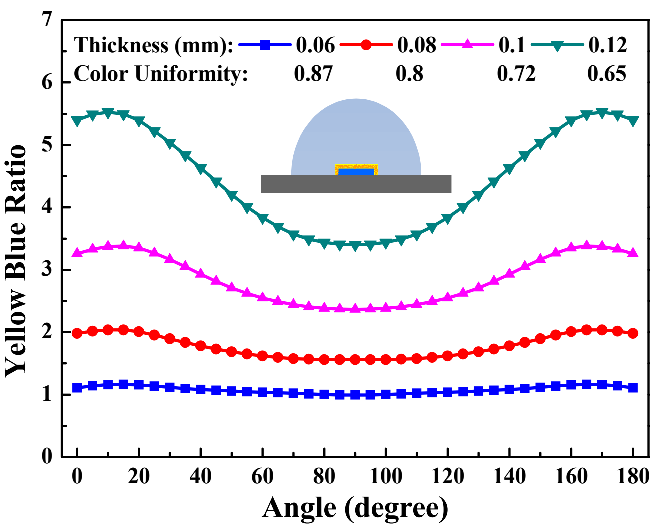


Figure 4. Effects of phosphor's thickness on the color distribution for the first structure.

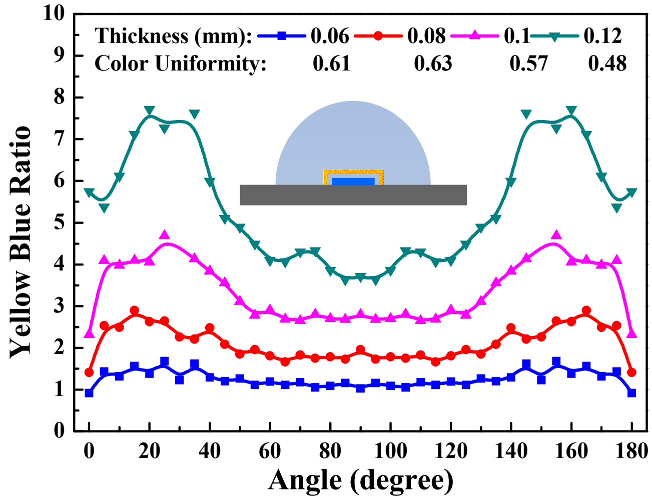


Figure 5. Effects of phosphor's thickness on the color distribution for the second structure.

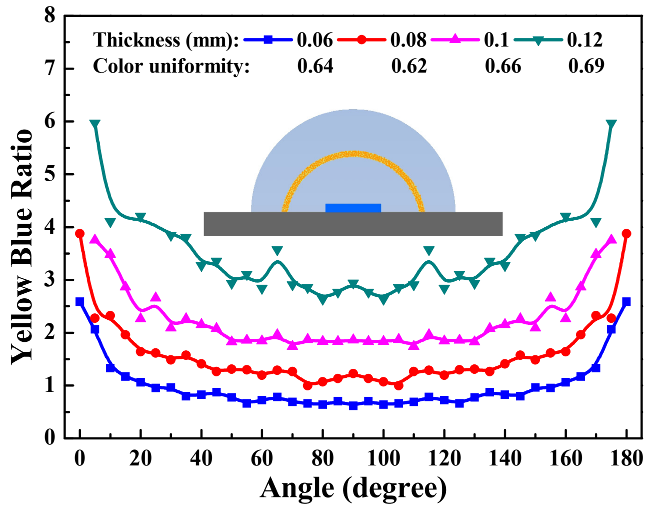


Figure 6. Effects of phosphor's thickness on the color distribution for the third structure.

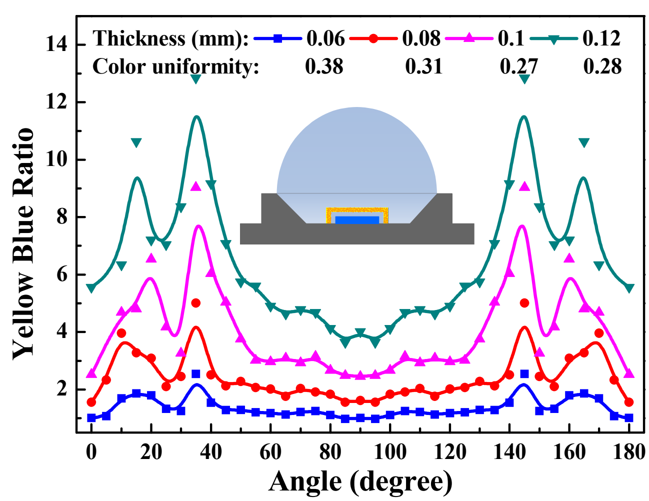


Figure 7. Effects of phosphor's thickness on the color distribution for the fourth structure.

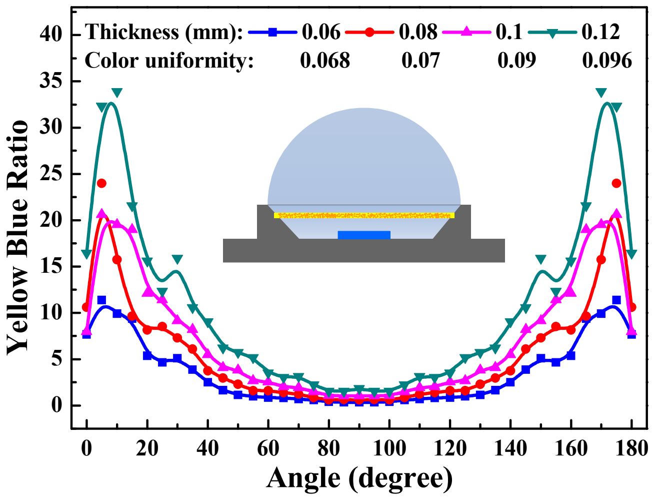


Figure 8. Effects of phosphor's thickness on the color distribution for the fifth structure.

The effects of phosphor's concentration on the color distribution are depicted in Figures 9-13. The results show that the concentration has almost the same influence on the color distribution. When the concentration increased, the yellow blue ratio curve is ascended. The rising tendency of the side angles is also more significant than that of central angles. The yellow ring will also appear and be more serious with the increase of concentration. The color uniformity for structures with reflector is also higher than other structures without reflector. However, there still are some different variations of the color distribution, which indicate that the concentration could affect the color distribution through different manner.

Firstly, once the concentration is more than the 19.85 mm^{-1}, the yellow blue ratio will jump up to be higher than 10. This color is almost yellow light and is not what the LED packaging desires. But if the concentration is lower than 19.85 mm^{-1}, the color of the LEDs is generally fluctuated in the acceptable ranges. Therefore, when considering the deposition of the phosphor particles in the silicone, the concentration should be paid special attention in the production to avoid generating partial high concentration areas.

Secondly, the variation of the color uniformity is not linearly reduced with the increase of concentration. In the second, third and fourth structures, the maximum value is among the middle concentration. In the fifth structure, the color uniformity is even linearly increased as that of thickness.

Thirdly, with the increase of the concentration, the variation of the color uniformity is bigger than that of thickness. For the structures with remote phosphor location, the variation is also significant. For example, in the third and fifth structures, the fluctuations are 21.7% and 45.5%. In the first case, the fluctuations are 10.1% and 29.2% with the increase of thickness. This indicates that the concentration could change the color distribution more effectively. This mainly dues to the enhanced scattering and absorption effects of phosphor.

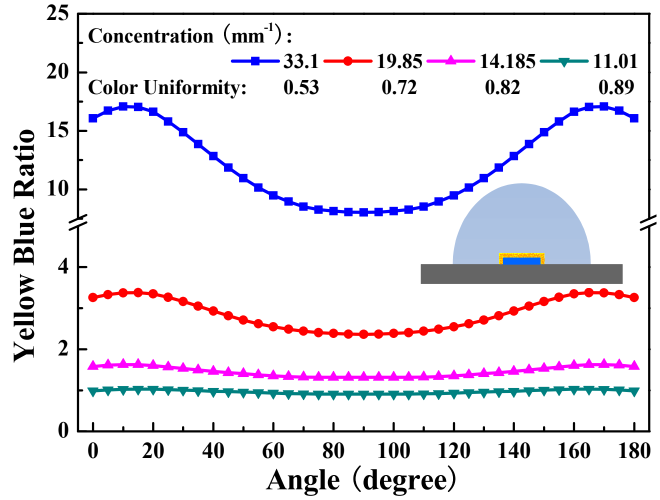


Figure 9. Effects of phosphor's concentration on the color distribution for the first structure.

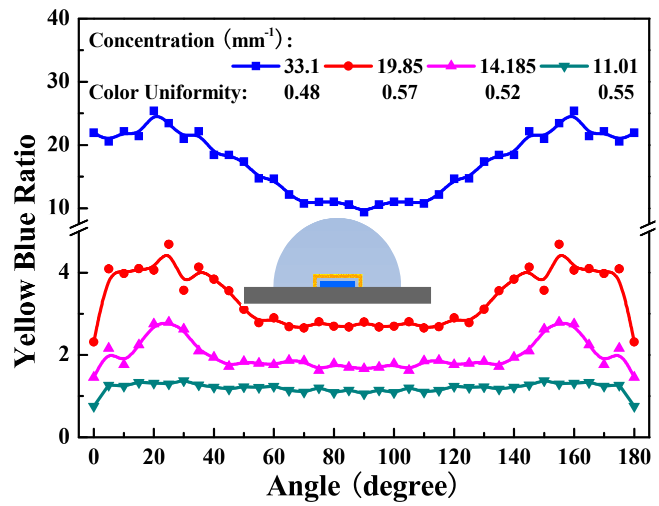


Figure 10. Effects of phosphor's concentration on the color distribution for the second structure.

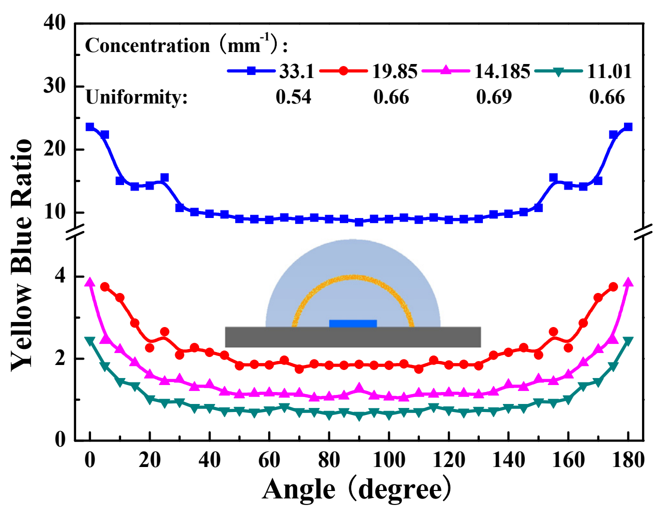


Figure 11. Effects of phosphor's concentration on the color distribution for the third structure.

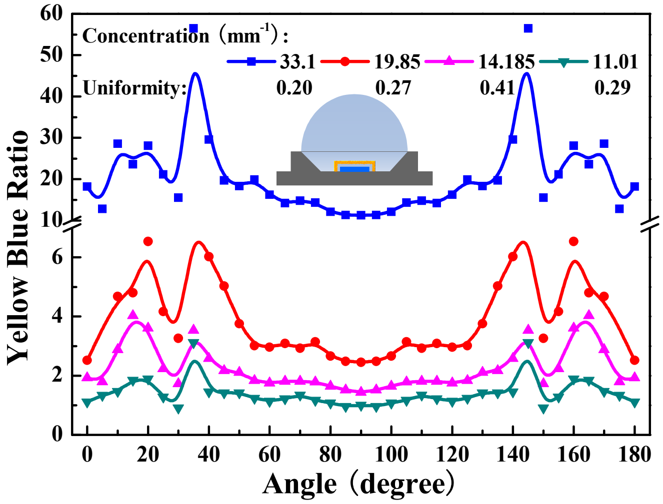


Figure 12. Effects of phosphor's concentration on the color distribution for the fourth structure.

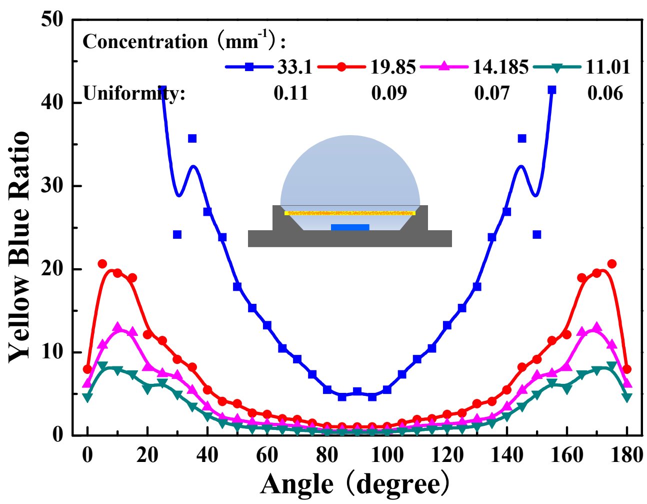


Figure 13. Effects of phosphor's concentration on the color distribution for the fifth structure.

Through the comparison of the effects of the two parameters in the phosphor layer, it can be conclude that the concentration has the biggest influence on the color distribution, the next factor is the thickness. Both the thickness and concentration could greatly affect the value of yellow blue ratio and the color distribution curve simultaneously. However, the concentration could influence the fundamental characteristics of phosphor more significantly. When the thickness and concentration are changed, the total effects of the absorption and scattering for the phosphor layer are also changed at the same time. Thicker or higher concentration layer could absorb and scatter more light rays, and thus increase the extracted yellow blue ratio. Therefore, small variation of the thickness and concentration will influence the color remarkably.

The another important factor affecting the color distribution is the optical structure. There are enormous differences whether the structure contains reflector and the shape of the phosphor layer is curved or not. The reflector reflects the side light rays and changes the rays to different directions. Since the light emitted from the chip is lambertian, most of the blue light could be extracted out without reflection. After the convergence of the lens, there is only a little blue light energy in the side angles. But the light emitted from the phosphor layer is arbitrary, part of the side yellow light could be reflected to the central angles while other parts could be reflected to the side angles. Therefore, the yellow blue ratio is reduced in central angles and increased in side angles. If there is not reflector, both of the blue light and yellow light could be converged by the lens without other disturbances. Although the emitted patterns for chip and phosphor are different, without the enhancement of the yellow light in the central and side angles, the differences are not as large as those cases with reflector. Therefore, the color uniformity is higher.

It can be found that the color uniformity of the third structure is more stable than other structures. This is due to the surface of the phosphor layer is curved. The curved surface could improve the critical angle for the light and provide more chance to let the rays extracted from the surface. In the third structure, the surface is hemispherical and the chip is located in the center. Therefore, the blue light emitted from the chip could keep the intensity distribution still like lambertian after passing through the phosphor layer. Since the phosphor layer and the lens are homocentric, the yellow light emitted from the phosphor layer could also easier emit out and keep the radiation pattern like what it is excited. That means the intensity distribution of the yellow light is near lambertian. The variations of the location, thickness and concentration could not change the fundamental effects of phosphor layer on the light propagation. Therefore, the color uniformity of curved surface is high and more stable.

Conclusions

Two parameters of the phosphor layer and six optical structures are discussed in this paper to analyze the factors affecting the color distribution of white light LEDs. Results show that the optical structure is the primary factor that deserves special attention. Reflector could reflect the side emitting light rays and change the rays to different directions. This shows that the color uniformity for the structures with reflector is lower. Another important factor is the shape of the phosphor layer. Hemispherical phosphor could improve the color uniformity and make the variation more stable. In the two parameters of the phosphor, the concentration has the biggest influence on the color distribution, the next factor is the thickness. Since small variation of the thickness and concentration could induce significant changes of the color, it should precisely control the steps of the fabrication technique of the phosphor to avoid generating serious yellow ring. In one word, it is difficult to improve the color uniformity only adjusting one or two factors. There needs more efforts on the studying of the influencing mechanism for the color distribution.

Acknowledgement

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