Design of a novel freeform lens for LED uniform illumination and conformal phosphor coating

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Abstract: A conformal phosphor coating can realize a phosphor layer with uniform thickness, which could enhance the angular color uniformity (ACU) of light-emitting diode (LED) packaging. In this study, a novel freeform lens was designed for simultaneous realization of LED uniform illumination and conformal phosphor coating. The detailed algorithm of the design method, which involves an extended light source and double refractions, was presented. The packaging configuration of the LED modules and the modeling of the light-conversion process were also presented. Monte Carlo ray-tracing simulations were conducted to validate the design method by comparisons with a conventional freeform lens. It is demonstrated that for the LED module with the present freeform lens, the illumination uniformity and ACU was 0.89 and 0.9283, respectively. The present freeform lens can realize equivalent illumination uniformity, but the angular color uniformity can be enhanced by 282.3% when compared with the conventional freeform lens.

OCIS codes: (230.3670) Light-emitting diodes; (220.3630) Lenses; (220.2945) Illumination design; (350.4600) Optical engineering.

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1. Introduction

Compared with traditional light sources, a white light-emitting diode (LED) has many advantages, such as high luminous efficiency, low power consumption, high reliability, and long life. Thus, LEDs are considered as a strong candidate for the next-generation light source and gradually are becoming widely used in our daily lives [1–5]. However, the direct output of an LED is usually a circle spot with non-uniform illuminance distribution, which makes it hard to meet the illumination requirement. Therefore, LED luminaries are generally required to re-distribute the spatial distribution of the LED's light energy through appropriate primary or secondary optics so that the light pattern and uniformity can be controlled for high-quality LED illumination [6,7]. A freeform lens is a type of newly emerging, non-imaging optics and has become a trend in LED optics design due to its advantages in abundant design freedom, compact size, and accurate light control. There exist many methods to deal with freeform lens design: the simultaneous multiple surface (SMS) method [7,8], the tailored freeform surface method [9], partial differential equations [10], the discontinuous freeform lens method [11–13], and the continuous freeform lens method [7,14–18]. These design methods, except for the SMS method, usually deal with the outer surface, and the inner surface is considered as a hemispherical shape for simplicity, which would abandon important design freedom in the

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inner surface of a freeform lens. Although the SMS method could deal with multiple freeform surfaces simultaneously by controlling the light directions, it is too complicated and could not guarantee the uniformity of the light–energy distribution.

On the other hand, uniform illumination is not the only requirement for high light quality of LED packaging; high angular color uniformity (ACU) is also required in many applications [19,20]. In the conventional phosphor-dispensing method, the geometry of the phosphor layer is usually convex, which leads to low ACU in the whole radiation angle. To overcome the poor ACU of the conventional phosphor-dispensing method, the conformal coating method was proposed in which the thickness of the phosphor layer is uniform. Currently, there are many methods to realize conformal coating: electrophoresis [21], slurry [22], settling [23], evaporating solvent [24], wafer-level coating [25], and capillary-assisted coating [26], for example. All of these methods have pros and cons—basically, they all need extra-process sequences or extra-process requirements to coat the phosphor layer onto the chip uniformly, and some of process sequences are difficult and some of the requirements are rigorous. Therefore, people both in industry and in academia still spend a lot of effort on the development of conformal phosphor-coating technology.

High-quality LED illumination, which requires high illumination uniformity, high ACU, and precise light pattern control, is in great demand by consumers and markets. Therefore, an optic design that can realize these requirements simultaneously has become a development trend. In this study, we designed a novel freeform lens for LED uniform illumination as well as realization of a conformal phosphor coating. The algorithm of the method involving the extended light source is presented in detail. The lighting performance of the present freeform lens is validated. Both the illumination uniformity and ACU were examined by Monte Carlo ray-tracing simulations.

2. Problem statement

As shown in Fig. 1(a), regardless of whether in the conventional freeform lens or in the hemispherical lens, the inner surface is hemispherical, which can make the lens design convenient and effective for a point light source. In order to coordinate the laying of conventional lenses in existing LED packaging processes, after the phosphor silicone matrix is dispersed onto the chip, silicone is put in the interspace between the substrate and the lens to expel the air and to protect the chips and the bonding wires. In these packaging processes, the non-uniform phosphor layer may lead to poor ACU in the whole radiation angle. On the other hand, the main advantage of the conformal phosphor coating lies in the uniform thickness of the phosphor layer.

Inspired by the existing packaging processes and the advantage of a conformal phosphor coating, one possible idea comes up: why not design a freeform lens in which the height of the inner surface is uniform? If so, we can realize a conformal phosphor coating by filling the interspace between the lens and the LED chip with a phosphor–silicone matrix. As shown in Fig. 1(b), if the inner surface of the freeform lens is flat, the thickness of the phosphor layer is uniform; thus, a conformal phosphor coating is realized.

With such a novel freeform lens, the packaging processes in the industry may even be facilitated and simplified. As shown in Fig. 1, the silicone-filling process can be integrated with the phosphor-coating process. After the novel lens is mounted, a phosphor–silicone matrix is filled into the interspace, which not only can realize a conformal phosphor coating, but also can play the role of silicone to protect the chip and bonding wires. If such a freeform lens is feasible, we can save packaging time and cost and improve manufacturing efficiency.

To design such a freeform lens with a uniform-height inner surface, we are faced with two inevitable problems. One is light control when the rays are refracted by the inner and outer surfaces through the lens; the other is the extended light source. The double refractions on the two surfaces make light control difficult, which should be designed well by considering the full light path from the light source to the target plane simultaneously. Since the thickness of the conformal phosphor coating layer is usually small, the LED chip could not be considered

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as a point light source any longer. The detailed design method is presented in the following sections.

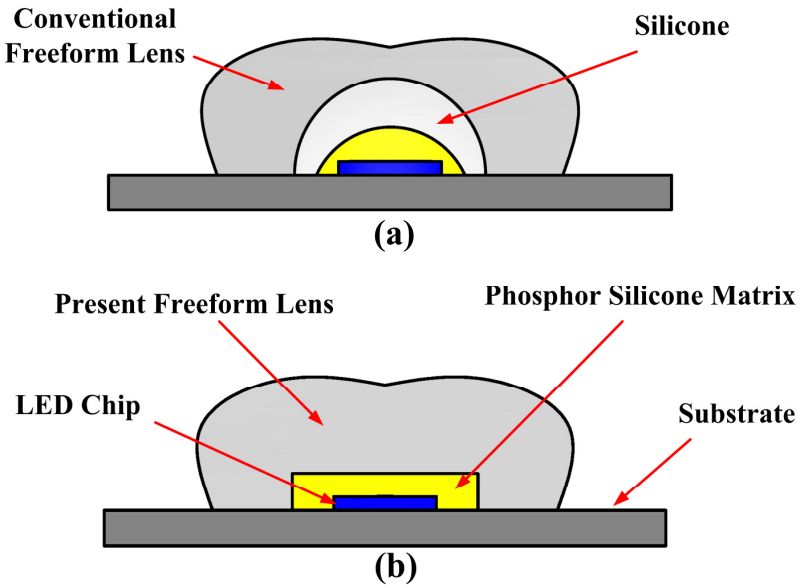

Fig. 1. (a) LED packaging module with conventional freeform lens, and (b) LED packaging module with novel freeform lens applied to conformal phosphor coating.

3. Design method for freeform lens for conformal coating

The design method consists of two main steps:

1. Establishing the light–energy mapping relationship between the light source and the target plane.
2. Constructing the freeform lens. A circular target plane is adopted as the example in the following design, but the design method can also be extended to other target planes, such as a rectangular plane.

3.1 Establishing the light–energy mapping relationship

As shown in Fig. 2, the energy distribution of the light source is divided into $M \times N$ grids with equal luminous flux, where the latitude is divided into N parts and the longitude is divided into M parts. Due to the central symmetry of the energy distribution of the light source, the light energy of each grid at the same latitude is the same. Then we can integrate the N grids along the latitude together and just consider the M parts along the longitude. According to the principle of photometry, the luminous flux of the unit area of the M parts $\Phi(\theta)$ and the total light source Φ_{total} can be calculated as Eq. (1) and Eq. (2), respectively.

$$\Phi(\theta) = \int_0^{2\pi} \int_{\theta_i}^{\theta_{i+1}} I(\theta,\varphi) \sin\theta d\theta d\varphi, \tag{1}$$

$$\Phi_{total} = \int_0^{\frac{\pi}{2}} \Phi(\theta) d\theta, \tag{2}$$

where $I(\theta)$ is the light intensity, and θ and φ are the notions shown in Fig. 2. The edge angle θ_i ($i = 1,2,...,M$) of each part, which defines the direction of edge light of each source grid, can be calculated by Eq. (3). Thus the light source is divided into M parts with equal luminous flux.

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$$\int_0^{\theta_i} 2\pi I(\theta)\sin\theta d\theta = i\frac{\Phi_{total}}{M}, (i = 1, 2, .., M). \quad (3)$$

To overcome the problem of lighting-performance deterioration caused by an extended light source and the scattering of phosphor particles, we divide the target plane into M concentric rings with unequal areas by inserting optimization coefficient C_i. For an arbitrary circle area with a radius of r_i, it is the summation of i concentric rings and we can obtain

$$\pi r_i^2 = iC_i\frac{\pi L^2}{M}, (i = 1, 2, .., M). \quad (4)$$

Thus the radius r_i of each concentric ring on the target plane can be calculated as

$$r_i = L\sqrt{\frac{iC_i}{M}}. \quad (5)$$

The purpose of introducing optimization coefficients is to optimize the light–energy distribution on the target plane to compensate for the illumination deterioration caused by the extended light source and the scattering of phosphor particles. The optimization coefficients must be equal to 1 when dealing with point light-source problems. During the design for the extended light source, we adjust C_i to make the trend of illumination distribution on the target plane to be the inverse of the trend of light-performance deterioration caused by the rays emanating from the edge area of the LED chip. However, it should be noted that the assignment of C_i is not arbitrary. Since the radius of the arbitrary circle area r_i is incremental, according to Eq. (5), the series $\{iC_i\}$ must be an ascending series. The last term of the series MC_M must be the largest, and at this situation, r_M must equal to L; thus, C_M must be 1. Therefore, each term of $\{iC_i\}$ must be less than M. According to the edge ray principle, rays from the edge of the light source should strike the edge of the target [14]. With the above gridding method, we can establish the light–energy mapping relationship between the extended light source and the target plane. As a result, we can obtain the edge angle θ_i and the corresponding radius r_i of each ray.

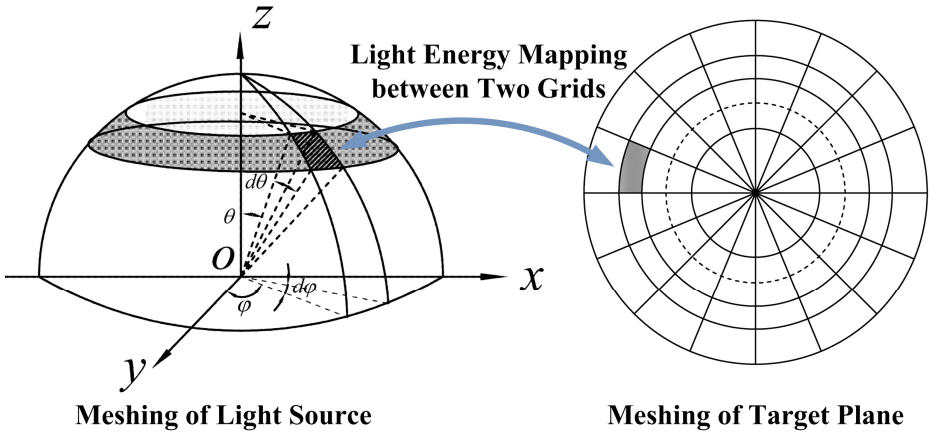

Fig. 2. Schematic of light–energy mapping between the light source and the target plane.

3.2 Constructing the freeform lens

Since both the target plane and the light intensity distribution of the light source are central symmetrical, the lens could also be designed as centrally symmetrical Figure 3 shows the typical light path from the light source to the target plane through the present freeform lens. As shown in Fig. 3, the incident ray $\overrightarrow{OA}$ is refracted to $\overrightarrow{AB}$ by the inner surface, then $\overrightarrow{AB}$ is refracted by the outer surface, and the output ray $\overrightarrow{BR}$ irradiates at the corresponding point R on

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the target plane. According to Snell's law, the ray $\overrightarrow{OA}$, $\overrightarrow{AB}$, and $\overrightarrow{BR}$ must satisfy the following equations: [6]

$$n_1 \frac{\overrightarrow{OA}}{\left|\overrightarrow{OA}\right|} \times \overrightarrow{N_1} = n_2 \frac{\overrightarrow{AB}}{\left|\overrightarrow{AB}\right|} \times \overrightarrow{N_1}, \tag{6}$$

$$n_2 \frac{\overrightarrow{AB}}{\left|\overrightarrow{AB}\right|} \times \overrightarrow{N_2} = n_3 \frac{\overrightarrow{BR}}{\left|\overrightarrow{BR}\right|} \times \overrightarrow{N_2}, \tag{7}$$

where $\overrightarrow{N_1}$ and $\overrightarrow{N_2}$ are the unit normal vectors of the inner surface and outer surface, respectively; n_1, n_2, and n_3 are the refractive indices of each area, respectively; n_1 is the refractive index of the phosphor silicone matrix; n_2 is the refractive index of the lens material; and n_3 equals 1.00 because the area is air.

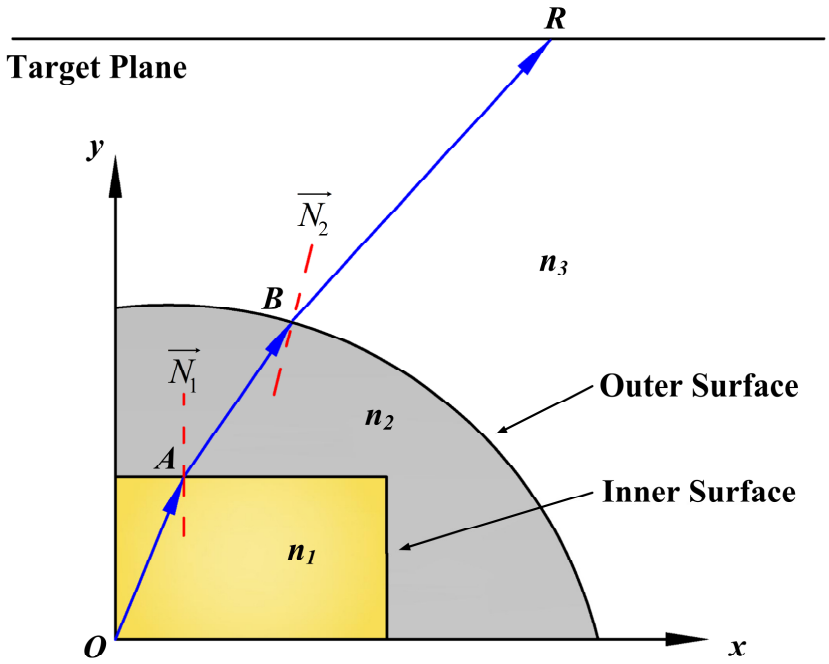

Fig. 3. Schematic of typical light path from the light source to the target plane through the present freeform lens. The inner surface is a cylinder and the outer surface is freeform.

To be more specific, in this design the inner surface is a cylinder with a radius of a and a height of b. Therefore, as shown in Fig. 4, there exists a turning point A_T on the inner surface. The edge angle of the incident ray corresponding to A_T is denoted as θ_T, which can be determined by $\theta_T = arctan(a/b)$. According to relationship between the edge angle of the incident angle θ_i *and* θ_T, the inner surface can be divided into two cases:

- Case I: when the edge angle θ_i is less than θ_T, the light path is illustrated as the light path of "O-A_i-B_i-R_i".
- Case II: when the edge angle θ_j is larger than θ_T, the light path is illustrated as the light path of "O-A_j-B_j-R_j".

In both cases, the refractions happening on the inner and outer surfaces are controlled by Snell's law, and Eq. (6) and Eq. (7) could be rewritten as Eq. (8) and Eq. (9) with the notions in Fig. 4.

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$$n_1 \sin \alpha_x = n_2 \sin \beta_x, (x = i, j), \tag{8}$$

$$n_2 \sin \psi_x = n_3 \sin \omega_x, (x = i, j). \tag{9}$$

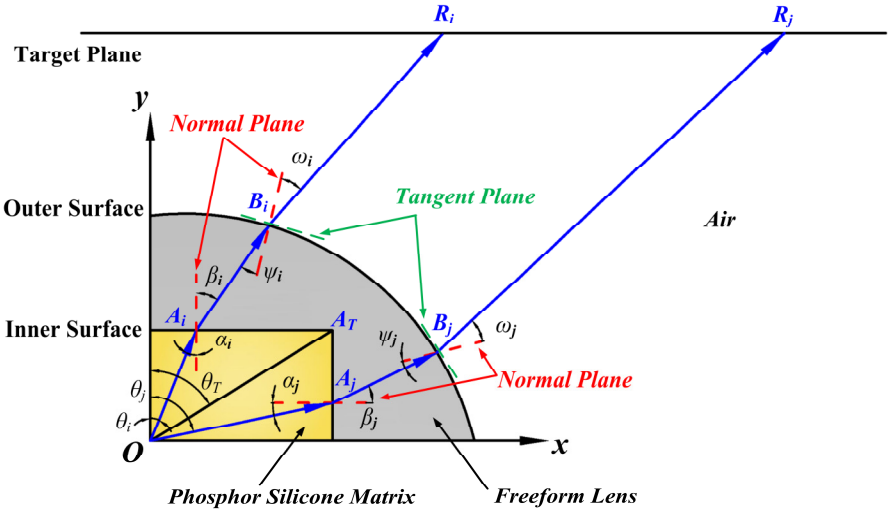

Fig. 4. Specific light paths from the light source to the target plane through the present freeform lens. Phosphor silicone matrix is filled in the interspace between the light source and inner surface of the lens. Blue lines are the typical light paths. Red dashed lines are the normal plane and green dashed lines are the tangent plane. Point A_T is the turning point of the inner surface. $\alpha_x(x = i,j)$ and $\beta_x(x = i,j)$ are the incident angle and refraction angle on the inner surface, respectively. $\psi_x(x = i,j)$ and $\omega_x(x = i,j)$ are the incident angle and refraction angle on the outer surface, respectively.

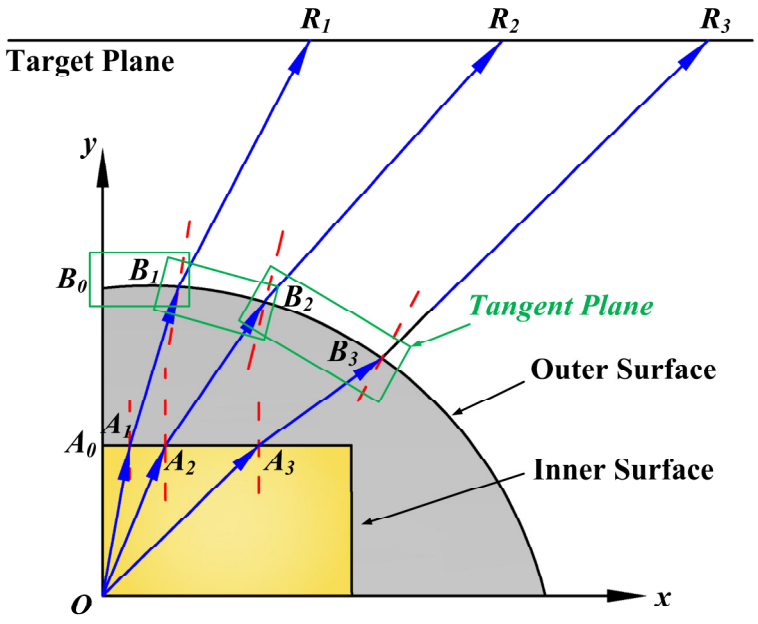

Fig. 5. Schematic of point generation on the outer surface of the present freeform lens. Red dashed lines are the normal plane and green boxes are the tangent plane of the points on the outer surface.

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In *Case I*, when the inner surface is given, the coordinates of A_i can be denoted as ($b \times \tan\theta_i$, b). From the geometrical relationship in Fig. 4, α_i equals θ_i; therefore, the vector $\overrightarrow{A_iB_i}$ can be calculated by solving β_i in Eq. (8). To obtain the coordinates of points B_i on the outer surface, as shown in Fig. 5, we first fix an initial point B_0 as the vertex of the outer surface of the lens, and the normal vector at this point is vertical up. The second point B_1 can be calculated by the intersection of the incident ray $\overrightarrow{A_1B_1}$ and the tangent plane of the point B_0. Since the corresponding point R_1 was determined previously, according to Eq. (7), we can then calculate the unit normal vector on point B_1 on the outer surface and consequently obtain the tangent plane. The tangent plane on point B_1 can help obtain the coordinates of the next point B_2. By repeating this process until the edge angle θ_i approaches θ_T, we can get all of the points B_i and their unit normal vectors on the outer surface.

In *Case II*, the coordinates of A_j can be denoted as (a, $a \times \cot\theta_j$). From Fig. 4, α_j equals to ($\pi/2$-θ_j), therefore the vector $\overrightarrow{A_jB_j}$ can also be calculated by solving β_j in Eq. (8). With the similar method in *Case I*, we could obtain the coordinates of B_j on the outer surface.

After obtaining all of the coordinates of points on the outer surface, we fit these points to generate the contour line of the lens's cross section by applying the lofting method [27], and we then get the freeform lens by rotating the contour line around the symmetry axis.

4. Simulation methodology

To validate the above design method, we designed a freeform lens to realize a conformal phosphor coating. As a comparison, we also built a conventional freeform lens. The lighting performance, including the illumination uniformity and the ACU of these two lenses, was examined. This section will be followed by a detailed description of simulation models, including the packaging configuration and the chip structure. Then we present the simulations process, especially the simulation of color conversion in a phosphor–silicone matrix.

4.1 Model setup

As shown in Fig. 1, we built two LED module models: one with the present freeform lens and the other with the existing conventional freeform lens. It is seen that the inner surface of the present freeform lens was a cylinder and the outer surface was freeform. The radius of the cylinder was 0.8 mm and its height was 0.4 mm. The initial height of the outer surface was 2 mm. Figure 6(a) shows the specific packaging configuration of an LED module with the present freeform lens with consideration of a phosphor–silicone matrix. As mentioned above, the phosphor–silicone matrix was placed between the LED chip and the freeform lens, so therefore its shape was also cylindrical and the thickness was 0.3 mm. While in the conventional freeform lens, the outer surface was freeform while the inner surface was hemispherical. The initial height of the outer surface was also 2 mm and the radius of the inner surface was 1 mm. The material of these two lenses was selected as polymethyl-methacrylate (PMMA) and its refractive index is 1.4935.

Besides the above models, we also built a precise model of the LED chip. In this study, the LED chip was a conventional GaN chip and its typical structure is shown in Fig. 6(b). The thickness and composites of different layers were sketched, and the chip size was 1 × 1 mm. The luminescent multi-quantum well (MQW) was sandwiched by an n-GaN layer and a heterostructure of a p-GaN layer and a p-AlGaN layer. A curren-spreading layer fabricated by indium tin oxide (ITO) and a sapphire substrate were also taken into consideration. The top and bottom surfaces of the MQW were set as luminescent surfaces with Lambertian light distribution. The absorption coefficients and refractive indices for p-GaN, MQW, and n-GaN were 5, 8, and 5 mm^{-1} and 2.45, 2.54, and 2.42, respectively [28,29]. The reflection coefficient of the reflecting layer (Ag) was set as 0.95. By setting the absorption coefficients and refractive indices of the materials, the precise model of a conventional GaN blue LED chip could be achieved successfully.

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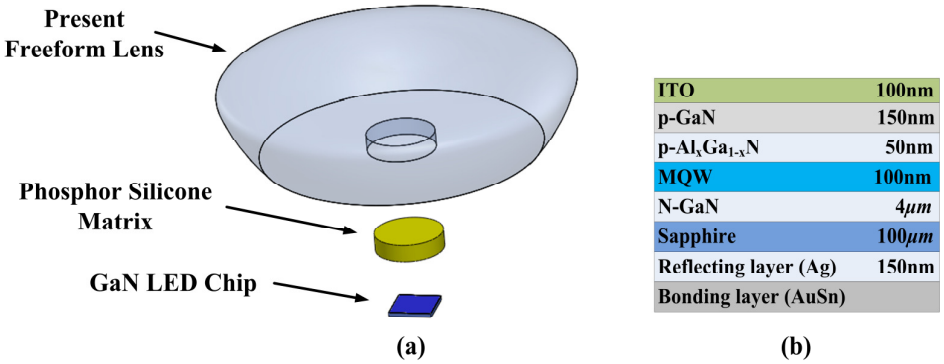

Fig. 6. (a) Packaging configuration of LED module with present freeform lens. (b)Structure of conventional GaN LED chip.

4.2 Simulation process

After building the models of these two LED modules, Monte Carlo ray-tracing simulations were used to validate the lighting performance, including the illumination uniformity and the ACU. In the Monte Carlo ray-tracing simulation, 1 million rays from randomly selected points on the surfaces of the light source strike into randomly selected angles in the space. The selections of starting points and ray direction are based on probabilistic functions that describe the emissive characteristics of the light sources [6]. In all of the simulations, the distance between the light source and the target plane was 50 mm and the radius of the target plane was also 50 mm. According to the simulation results, we optimized the coefficients C_i until the lighting performance satisfied the requirements of some specific applications.

As for the simulation of a phosphor–silicone matrix, the phosphor particles can absorb part of the blue light emanating from the LED chip and re-emit a yellow light. The rest of the blue light and the yellow light can mix with each other, and white light is therefore produced. The quantum efficiency of the phosphor was assumed to be 80%, which means 0.8 photons of the converted yellow light could be re-emitted from the phosphor particle when one blue photon was absorbed by one phosphor particle [30,31]. The detailed parameters of the phosphor, especially the absorption coefficients and scattering coefficients, were obtained from the Mie theory [32,33]. The wavelength-dependent refractive indices, absorption, and scattering coefficients, which varied with the changes of phosphor concentration, played important roles in determining the optical performance of the LED packages. In this study, to make the simulation closer to reality, the phosphor concentration was set as 0.16 g/cm^3. The necessary parameters in the simulations can be found in our previous works [28,29,32–34]. For modeling the light conversion process, the rays of blue and yellow light were simulated separately by the Monte Carlo ray-tracing method. In the simulation, two wavelengths were ray traced separately, namely 465 nm and 555 nm, which represent the blue LED light and the phosphor-converted yellow light, respectively [28,29]. The blue light emanated from the top surface of the chip and the yellow light was emitted from the volume of phosphor silicone matrix according to the distribution of phosphor particles inside the silicone matrix.

5. Results and discussions

The lighting performance comparisons between these two LED modules are shown in Fig. 7 and Fig. 8, respectively. The irradiance profiles in both results were normalized to peak irradiance. From Fig. 7 and Fig. 8, it is noticed that the bright regions in both figures are very large and the irradiance profiles are flat in the center region. The illumination uniformity was calculated as the ratio of average irradiance to the maximum irradiance, and the values were 0.89 and 0.90 in Fig. 7 and Fig. 8, respectively. It can be seen that the present freeform lens

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had equivalent illumination uniformity as that of a conventional freeform lens; thus, its lighting performance could satisfy the requirements of most applications.

We introduced the yellow-blue ratio (YBR) to represent the variation of correlated color temperature (CCT) [20,29]. The higher the YBR is, the larger the yellow light intensity is and the lower CCT is. The ACU can be calculated as the minimum YBR to the maximum YBR in the whole radiation angle. The light intensities of the two LED modules are illustrated in Fig. 9. From the comparison, it is seen that the YBR curve of the LED module with the present freeform lens was much flatter. For the comparative YBR curve, the YBR increased greatly in the edge region, which may lead to a "yellow ring" at the edge of light pattern. Hence, the ACUs were 0.9283 and 0.2428 for LED modules with the present freeform lens and conventional freeform lens, respectively. The ACU was enhanced by 282.3% after using the present freeform lens. It is concluded that the ACU could be enhanced by the present freeform lens extraordinarily.

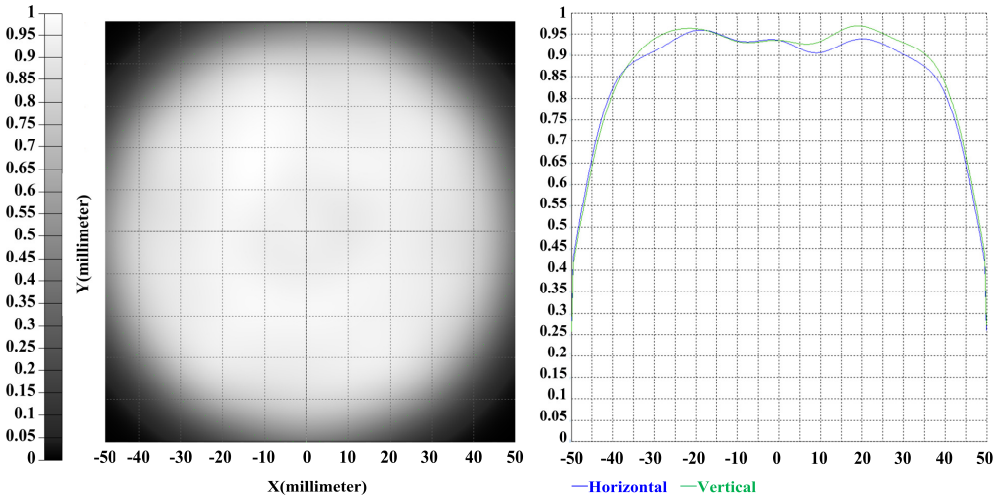

Fig. 7. Lighting performance of the present freeform lens.

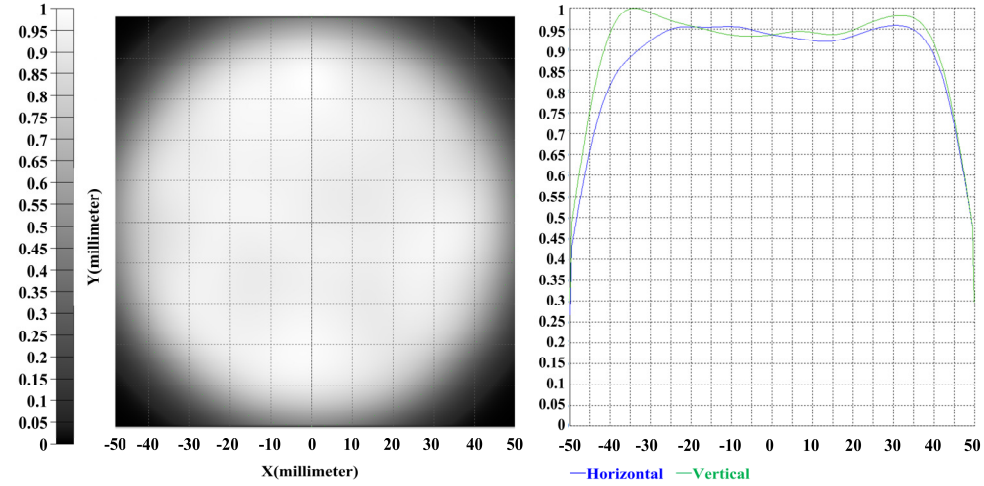

Fig. 8. Lighting performance of the conventional freeform lens.

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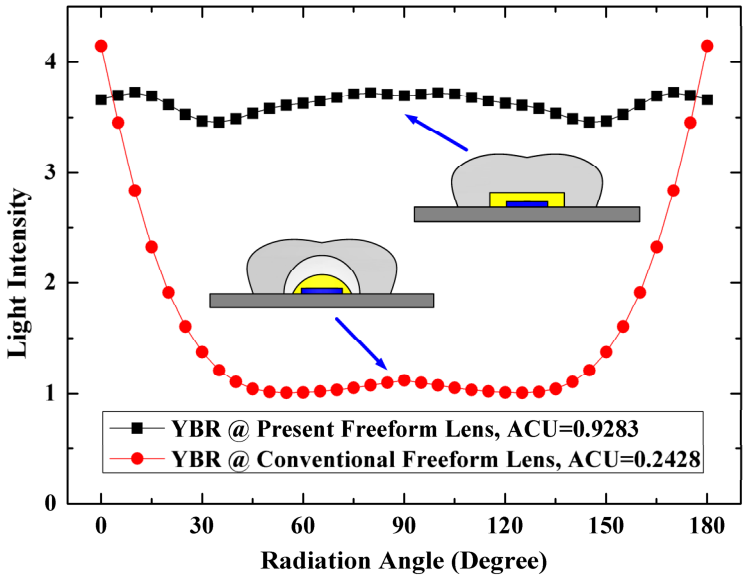

Fig. 9. Comparison of light intensity of YBR and ACU in the whole radiation angle between the LED modules with the present freeform lens and the conventional freeform lens.

6. Conclusions

In this study, a novel freeform lens, whose inner surface was a cylinder and whose outer surface was freeform, was designed for LED uniform illumination and realization of a conformal phosphor coating simultaneously. The algorithm of the design method was presented in detail, and Monte Carlo ray-tracing simulations were conducted for validation. By controlling the shape of the inner surface, we realized a thin conformal phosphor coating layer whose thickness was only 0.3 mm. It is demonstrated that the present freeform lens can realize equivalent illumination uniformity, but the angular color uniformity can be enhanced by 282.3% when compared with the conventional freeform lens. The illumination uniformity and angular color uniformity of the LED module with the present freeform lens were 0.89 and 0.9283, respectively.

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