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RESEARCH ARTICLE

Optical design of rectangular illumination with freeform lenses for the application of LED road lighting

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Abstract We present a freeform lens for application to light-emitting diodes (LED) road lighting. We propose a simple source–target luminous intensity mapping method based on Snell's law and geometric-optics analysis. We calculated different contours of cross-sections to construct a freeform lens with a smooth surface. The computer simulation results show that the lighting performance of a single freeform lens is not sufficient for road lighting. For the road lamp simulation, we adopted an oval arrangement of freeform lenses on a printed circuit board. In addition, we performed tolerance analysis to determine the tolerance limits of manufacturing and installation errors. A road lamp at a height of 12 m can create rectangular illumination with an area of 40 m × 12 m, 69.7% uniformity, and average illuminance of 24.6 lux. This lighting performance can fully comply with the urban road lighting design standard.

Keywords light-emitting diodes (LED), nonimaging optics, freeform lens design, rectangular illumination

1 Introduction

In numerous lighting situations, rectangular illumination is a common lighting requirement. At present, several methods can realize rectangular illumination, such as the fly-eye lens [1,2], micro-lens array [3–5], total internal reflection (TIR) lens [6,7], and freeform lens. The fly-eye lens is composed of a collimating system and fly-eye lenses. Each fly-eye lens has the same focal length and is embedded in a square base board. Although this method can provide rectangular illumination, the system structure is complex. The absorption from the material of multiple lenses is large, light energy is wasted, and the optical efficiency is low. The micro-lens array method uses a collimating system with a micro-lens array on top to achieve rectangular illumination. The collimating system employs a TIR collimating lens [3] or Fresnel lens [4] to converge the light from a LED and emit it in a small angle. The micro-lens array plays an important role in the redistribution of the beam angle and optical energy. Compared with the fly-eye lens method, the micro-lens array method provides more accurate light ray control. The system structure still contains two parts, which is relatively complex. The freeform lens technique is a common method to realize rectangular illumination directly. A system with a freeform lens has the advantages of small volume and a high degree of freedom in its design. Rectangular illumination with a TIR lens can be achieved by using composite ray mapping with a special structure of freeform lens. Traditional design methods of freeform surfaces can be classified as numerical solutions obtained by suitable group differential equations [8–11] and mapping between the source and the target [12–16]. The process of solving partial differential equations is complex and the solvability is poor, and this technique cannot solve all lens surfaces. In addition, this method cannot guarantee that every lens structure has a smooth optical surface. The mapping method needs to partition the source intensity distribution in spherical (θ, φ) coordinates or (u, v) coordinates and partition its corresponding target irradiance distribution into a grid. The illumination quality of a lens is directly determined by dense sampling at the source and target regions. The feedback modification method is typically used together with the mapping technique. This approach requires a large number of complex iterative calculations. Hu Run et al. used the mapping method to establish the ray relationship between the source and the target plane by using vectors. The source angle θ_i and the

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corresponding radius r_i of each ray were calculated with the energy conservation law. Although two freeform surfaces can be calculated simultaneously, the numerical solution is complex [17,18].

In this paper, we propose a simple source–target luminous intensity mapping method based on Snell's law and geometric-optics analysis to construct a freeform lens without performing complex iterative calculations or solving differential equations. According to the principle of energy conservation, we derived the relationship between the incident angle of light emitted from a LED and the emitted ray angle of the lens; this equation, which is simple, was established using the finite-difference method. We analyzed the initial conditions of a freeform lens at different cross-sections and used the cross-section contours to design the structure of the lens and achieve rectangular illumination. The obtained freeform lens has a smooth and continuous optical surface. Through simulations and tolerance analyses, the lighting performance of an oval lens arrangement on a printed circuit board (PCB) can fully satisfy the urban road lighting design standard.

2 Design principle

2.1 Geometric-optics analysis

The two-dimensional (2D) contour of an arbitrary refractive surface with negative tangential vector is defined in the Cartesian coordinate system, as indicated in Fig. 1. The angle between the y axis and a light ray emitted from the LED is θ_i, and the angle of the emitted ray with the vertical direction is θ_o. The incident angle on the freeform surface is θ_r and the refraction angle is θ_c. The angle between the tangential and horizontal directions at point P is θ_t. According to the geometric-optics analysis, we obtain

$$\theta_r = \theta_t - \theta_i, \tag{1}$$

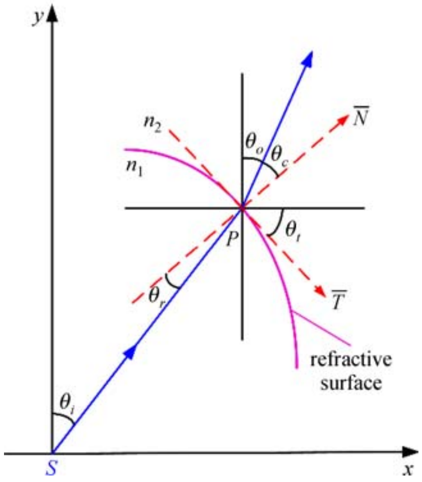


Fig. 1 Geometric-optics relation of refractive freeform surface

$$\theta_c = \theta_t - \theta_o. \tag{2}$$

Any light ray emitted from the LED in the medium with refractive index n_1 arrives at the freeform surface and is then refracted in the medium with refractive index n_2 according to Snell's law. The angles θ_r and θ_c must satisfy the following relation:

$$n_1 \sin\theta_r = n_2 \sin\theta_c. \tag{3}$$

By substituting Eqs. (1) and (2) into Eq. (3), we can obtain the tangent value of θ_t:

$$\tan\theta_t = \frac{n_1 \sin\theta_i - n_2 \sin\theta_o}{n_2 \cos\theta_o - n_1 \cos\theta_i}. \tag{4}$$

The relationship between the incident angle θ_i and the refraction angle θ_o can be derived by using source–target luminous intensity mapping. The detailed calculation process is given in the following subsection.

2.2 Construction of freeform surface

For a Lambertian-type LED, the light distribution can be expressed as

$$I_S(\theta) = I_0 \cos\theta, \tag{5}$$

where I_0 is the intensity of the radiation in an axis and θ is the angle between the emitted ray and the axis.

We assume that the distance between the source and the target plane in the axis is h. According to the basic photometry principle, the irradiance at the center of the target plane E_0 is

$$E_0 = \frac{I_0}{h^2}. \tag{6}$$

The irradiance E_θ produced by the light source at an angle θ to the axis is

$$E_\theta = \frac{I_\theta \cos^3\theta}{h^2}. \tag{7}$$

To achieve uniform illumination, the irradiance of all points on the target plane must be equal, namely, $E_0 = E_\theta$. Then, the target intensity distribution can be expressed as

$$I_T(\theta) = \frac{I_0}{\cos^3\theta}. \tag{8}$$

According to the energy conservation law, the flux emitted from the LED light source with an angle θ_i must be equal to that irradiated from the lens with an angle θ_o to the target plane. The integration range of the light source is $0 \leqslant \theta \leqslant \theta_i$, while that of the emitted ray angle from the lens is $0 \leqslant \theta \leqslant \theta_o$. We can obtain the following relation:

$$2\pi \int_0^{\theta_i} I_S(\theta) \sin\theta \, \mathrm{d}\theta = 2\pi \int_0^{\theta_o} I_T(\theta') \sin\theta' \, \mathrm{d}\theta'. \tag{9}$$

By substituting I_S from Eq. (5) and I_T from Eq. (8) into both sides of Eq. (9), the relationship between the angles θ_i and θ_o can be derived as

$$\sin\theta_i = \tan\theta_o, \tag{10}$$

where the range of the incidence angle θ_i is $0 \leqslant \theta_i \leqslant \pi/2$ and that of the emitted ray angle θ_o is $0 \leqslant \theta_o \leqslant \theta_{o\max}$. When θ_i equals $\pi/2$, the corresponding maximum emitted ray angle $\theta_{o\max}$ is 45°; $\theta_{o\max}$ is also defined as the half-beam angle of the lens. From Eq. (10), we can calculate the emitted ray angle θ_o for a given incidence angle θ_i. By substituting both values of θ_o and θ_i into Eq. (4), we can obtain the tangential equation of an arbitrary point on the freeform surface.

However, the maximum emitted ray angle $\theta_{o\max}$ is 45°, according to the above mapping. We propose a coefficient k that meets other emitted ray angle θ_o of the lens. When the length of the target plane in the wanted section direction of the lens is k times the length mentioned above, Eq. (9) can be rewritten as

$$2\pi\int_0^{\theta_i} I_S(\theta)\sin\theta \mathrm{d}\theta = 2\pi\int_0^{\theta_o} k\cdot I_T(\theta')\sin\theta' \mathrm{d}\theta'. \tag{11}$$

Therefore, the new relationship between the angles θ_i and θ_o is

$$\sin\theta_i = \sqrt{k}\tan\theta_o. \tag{12}$$

The emitted ray angle θ_o can be expressed as

$$\theta_o = \arctan(\sin\theta_i/\sqrt{k}). \tag{13}$$

When θ_i equals $\pi/2$, the corresponding maximum emitted ray angle $\theta_{o\max}$ is

$$\theta_{o\max} = \arctan(1/\sqrt{k}). \tag{14}$$

Consequently, a lens with arbitrary $\theta_{o\max}$ can be designed.

As shown in Fig. 2, the blue lines marked as r_0, r_1, r_2, and r_3 denote the incident light rays emitted from the light source S and arrive to the freeform surface at the points P_0, P_1, P_2, and P_3, respectively. P_0 is the initial point of the refractive freeform surface used for the iterative calculation and can determine the height of the freeform lens. The corresponding emitted ray angle can be derived from Eq. (10) or Eq. (12). The tangential equation of point P_0 is calculated from Eq. (4). $\Delta\theta$ is the incidence angle increment in the calculative process. When $\Delta\theta$ is infinitesimal, point P_1 can be regarded as the intersection of the incident light ray r_1 and the tangential vector $\overline{T_0}$. The emission angle θ_{o1} is calculated again using Eq. (10) or Eq. (12) and the tangential equation of point P_1 is obtained from Eq. (4). The coordinate of P_2 is calculated after obtaining that of P_1. By repeating the above process until θ_i equals $\pi/2$, a 2D contour of the freeform surface can be constructed [19].

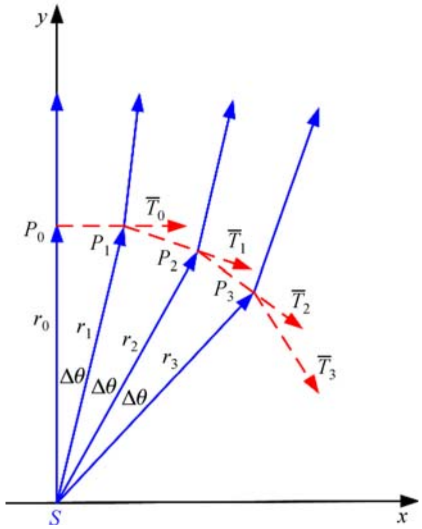


Fig. 2 Construction of 2D contour of freeform surface

3 Road lighting design

In contrast to circular illumination, the emitted ray angles of a lens in the transverse and longitudinal directions are different in rectangular illumination. A batwing-type light distribution is usually applied in road lighting; this can reduce the illuminance under the street lamp and increase it on the road between street lamps to make the road lighting uniform. Therefore, we must calculate framework counters of the freeform lens in different cross-sections to construct the three-dimensional (3D) entity model.

3.1 Construction of freeform lens

The emitted ray angle of the lens in cross-section A-A must cover the width of a rectangular spot. The counter of cross-section A-A is composed of the spherical surface 1 and the refractive freeform surface 2. The spherical surface 1 does not change the exit beam angle from the LED. As indicated in Fig. 3, if $P(x, y)$ is an arbitrary point on the surface, NN indicates the normal of point P, KK denotes the tangent line of point P, VV is the vertical line through point P, HH is the horizontal line through point P, and γ is the angle between the tangent line KK and the horizontal line HH. Point A is the initial point of surface 2. According to the edge-ray principle, rays from the edge of the source should strike the edge of the target. In Fig. 3, θ represents the angle between the emitted ray and the vertical line to the source and φ denotes the angle between the emitted ray from the lens and the vertical line to the freeform surface. When the emitted ray angle θ_i is $\pi/2$, the corresponding emitted ray angle to the vertical line is $\varphi_{\max}$. Rays with angle $\varphi_{\max}$ represent the edge rays of the freeform surface. As the target plane has a certain size, the emitted ray $\varphi_{\max}$

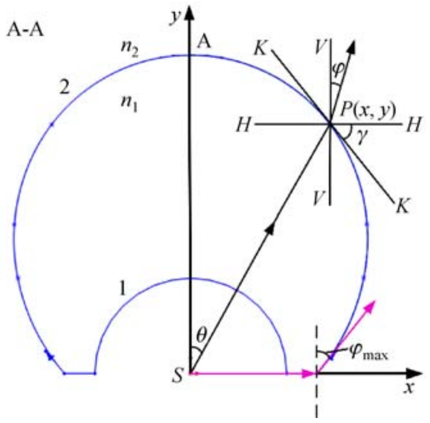


Fig. 3 Freeform surface for cross-section A-A

is always positive. Thus, we can obtain the expression of the coefficient k for cross-section A-A:

$$k=\left(\frac{1}{\tan\varphi_{\max}}\right)^2. \tag{15}$$

Then, the coordinates of every point on the counter of the freeform surface can be calculated for cross-section A-A by using the method mentioned above.

Similarly, in Fig. 4, the emitted ray angle of the lens in cross-section B-B must cover the length of a rectangular spot. In Fig. 4, Point B is the initial point of surface 2 and the y-coordinates of point B and point A are equal. To distinguish the emitted ray angle of the lens in cross-section B-B from that in cross-section A-A, we denote the emitted ray angle of the lens in cross-section B-B as δ. The maximum emitted ray angle is $\delta_{\max}$ and the coefficient k of cross-section B-B is

$$k=\left(\frac{1}{\tan\delta_{\max}}\right)^2. \tag{16}$$

For an arbitrary angle θ of a ray emitted from the LED, we can calculate the emitted ray angle δ of point P in cross-section B-B.

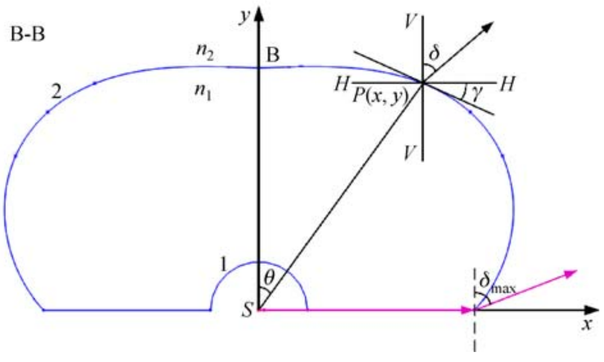


Fig. 4 Freeform surface for cross-section B-B

$$\delta=\arctan\left(\frac{\sin\theta}{\sqrt{k}}\right). \tag{17}$$

Similarly, the coordinates of every point on the counter of the freeform surface can be calculated for cross-section B-B.

However, the 3D entity model of the freeform lens cannot be constructed only with two freeform surfaces for cross-sections A-A and B-B. Counters of other cross-sections corresponding to the z-axis with θ must also be calculated, as shown in Fig. 5. θ is the angle between the z-axis and the symmetrical axis of other cross section. Here, we calculate the counters of freeform surfaces with θ= 15°, 30°, 45°, 60°, 75°, 90°.

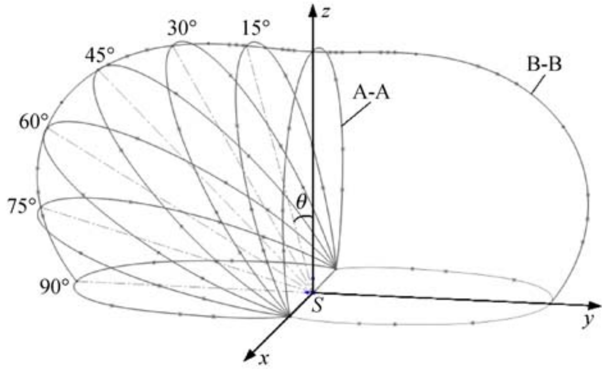


Fig. 5 Cross sections corresponding to cross-section A-A with different angles

In the process of calculating the coordinates of other cross-sections, the intersection $P_i(x_i,\ y_i)$ of the incident light ray emitted from the LED with θ_i and the counter of cross-section B-B should be calculated first. The y-coordinates of the initial point for other cross-sections are $m_i=\sqrt{x_i^2+y_i^2}$. Then, we must obtain the maximum emitted ray angle $\varphi_{i\max}$ for other cross-sections. We assume that the half-length of the target plane is L and its half-width is W. The vertical height between the central point S and the target plane is h. δ_i is the emitted ray angle of a ray emitted from the LED with angle θ_i that is refracted from cross-section B-B, and h_i is the distance between the central point S and the target plane in the direction of different cross-sections. In Fig. 6, we can get the following relationship from the geometric-optics analysis.

$$\tan\varphi_{\max}=\frac{W}{h}, \tag{18}$$

$$h_i=\frac{h}{\cos\delta_i}, \tag{19}$$

$$\tan\varphi_{i\max}=\frac{W}{h_i}. \tag{20}$$

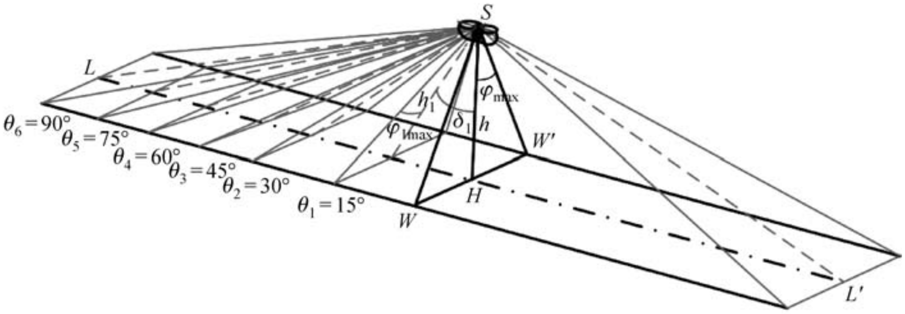


Fig. 6 Position of the light rays of the lens in the direction of different cross-sections

The relationship between $\varphi_{i\max}$ and δ_i can be calculated by solving Eqs. (18)–(20).

$$\tan\varphi_{i\max} = \cos\delta_i \tan\varphi_{\max}, \tag{21}$$

where $\varphi_{\max}$ is the maximum emitted ray angle of cross-section A-A. From Eq. (21), we can see that the maximum emitted ray angle $\varphi_{i\max}$ of different cross-sections is not related to the size of the target plane, but only depends on $\varphi_{\max}$ and δ_i. Based on the edge-ray principle, a light ray emitted from the edge of the source should propagate to the edge of the target plane. Therefore, light rays refracted from cross-section B-B are aligned in sequence on the target plane as shown in Fig. 6. Therefore, when we know the angle θ_i of a cross-section, we can calculate the corresponding emitted ray angle δ_i. Then, we can obtain the maximum emitted ray angle $\varphi_{i\max}$ in the direction of that cross-section by using Eq. (21). If m is the y-coordinate of the initial point, the coordinates of every point on the counter of the freeform surface can be calculated for other cross-sections by using the same method as that used for cross-section A-A. A lens entity can be constructed by using these counters as a framework and enveloping a layer of the surface.

3.2 Lens model and simulation

A freeform lens with emitted ray angle ±30° for cross-section A-A and ±60° for cross-section B-B was designed for road lighting. Assuming the initial coordinates of point A are (0, 10) for cross-section A-A, the same values correspond to the initial coordinates of point B for cross-section B-B. The material of the lens is polymethylmethacrylate and the calculated 2D freeform counters of cross-sections A-A and B-B are shown in Fig. 7. Because the half-beam angle of cross-section B-B is 60°, the coefficient k of cross-section B-B is 1/3. The values of m and $\varphi_{\max}$ can be obtained for different cross-sections and the calculated parameters are shown in Table 1. Then, the coordinates of different cross-sections can be calculated through the parameters m and k presented in Table 1.

The 2D contours of these refractive surfaces are defined in the same Cartesian coordinate system for different cross-sections. We can obtain the relative position and shape of these counters from Fig. 8. The 3D lens entity is modeled by SolidWorks software, as described in Fig. 9. In the 3D modeling process, we adopt the counters of cross-sections A-A and B-B as the two main orthogonal counters. The counter of cross-section A-A and those with θ = 15°, 30°, 45°, 60°, 75°, 90° to cross-section A-A are used as the framework, while the counter of cross-section B-B is used as the guideline. Then, the freeform lens entity can be constructed by using these counters as the framework and enveloping a layer of the surface. The freeform surface of the lens is smooth and continuous.

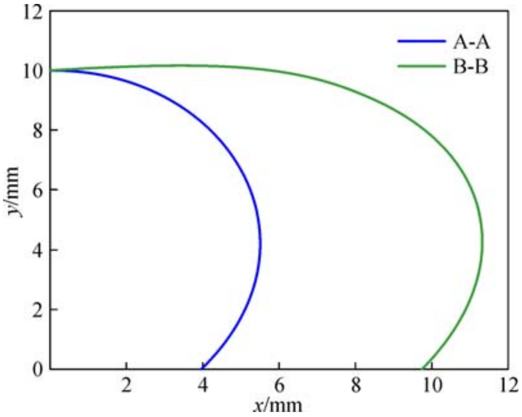


Fig. 7 Two-dimensional freeform counters of cross-sections A-A and B-B

Table 1 Parameters of different cross-sections

θ	δ	m/mm	$\varphi_{\max}$	k
0°	0°	10	30°	3
15°	24.15°	10.47	27.78°	3.6
30°	40.89°	11.51	23.58°	5.25
45°	50.77°	12.46	20.06°	7.5
60°	56.31°	12.61	17.76°	9.75
75°	59.13°	11.59	16.5°	11.4
90°	60°	9.74	16.1°	12

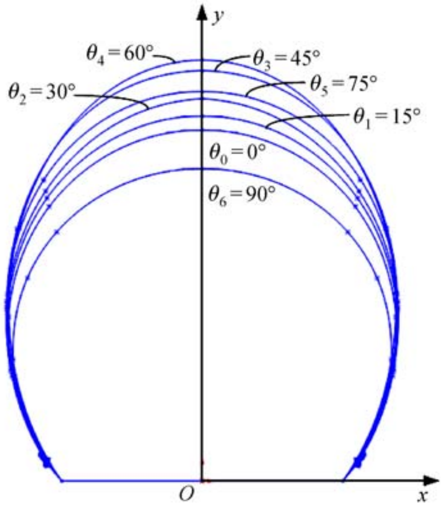


Fig. 8 Two-dimensional contours of different cross-sections

The design of this freeform surface lens is based on an ideal point source. However, in practical situations, the effect of the size of the LED chip on the lighting performance must be considered. Figure 10 shows the influence of the LED chip size on the uniformity and the efficiency of the lens. Assuming that the LED chip is square, the uniformity increases by changing the LED chip size from 0.01 to 2 mm. Additionally, the efficiency decreases from 86.1% to 73.1%, which is the opposite trend of that observed for the uniformity. Although a smaller chip size has good performance regarding efficiency, the uniformity decreases. To evaluate the design results, a 1 mm × 1 mm LED chip with total flux 100 lm and Lambertian-type radiation was used in the simulation. The illuminated plane was located at 12 m from the LED source to meet the requirements of road lighting. Based on the emitted ray angles of the freeform lens, rectangular illumination with a size of 40 m × 12 m can be obtained. Namely, a road lamp using the freeform lens described above can achieve a rectangular spot for a road length of 40 m and a road width of 12 m. Figure 11 shows the ray tracing results of the freeform lens.

The illuminance distribution at 12 m distance from the source on the target plane is shown in Fig. 12(a); the optical efficiency of the freeform lens is 80.2% and the average illuminance of the illumination area is 0.18 lux. Rectangular illumination in areas of 40 m length and 12 m width on both sides of the road is obtained. The illuminance uniformity of the illumination area is 67.4%, which is higher than the uniformity requirement of 40% of the urban road lighting design standard. Figure 12(b) shows the polar candela intensity distribution curve of the freeform lens. The light intensity in the far-field angle distribution is of the batwing type. The half-beam angle is 60° in the direction of the road and 30° in the direction vertical to the road. This result shows that the freeform lens design method described in this paper can meet the requirement for rectangular illumination.

According to the regulation of the urban road lighting design standard, the average illuminance of the illumination area must be higher than 20 lux. However, the average illuminance of a single freeform lens is only 0.18 lux. To meet the requirement, we can place the freeform lenses in the same direction in a certain regular arrangement. Provided that the direction of lenses is the same, the lenses can be arranged in a variety of ways, such as a rectangular arrangement, circular arrangement, oval arrangement, star-like arrangement, or any other arrange-

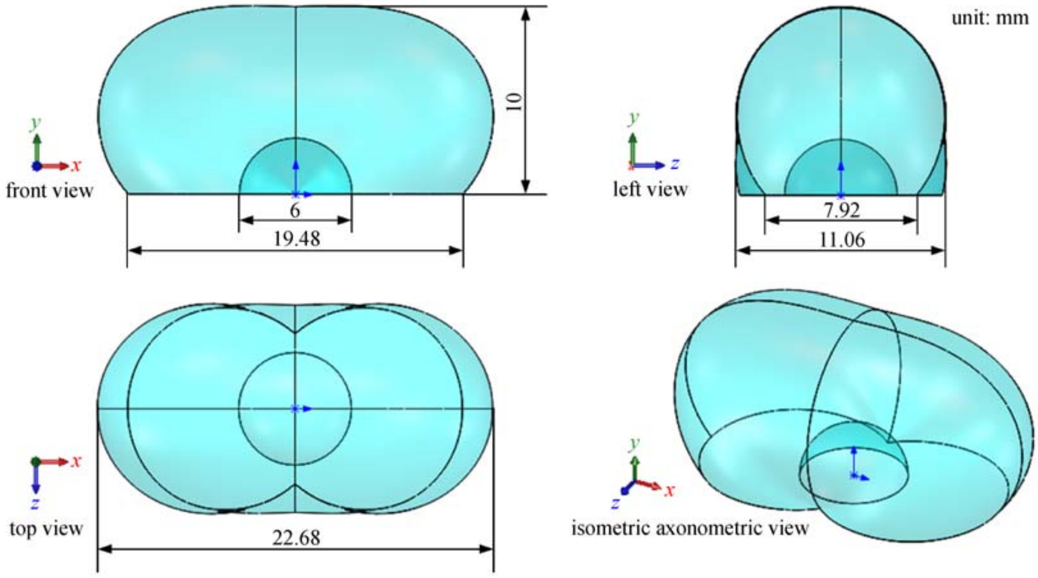


Fig. 9 Three-dimensional entity model of the freeform lens

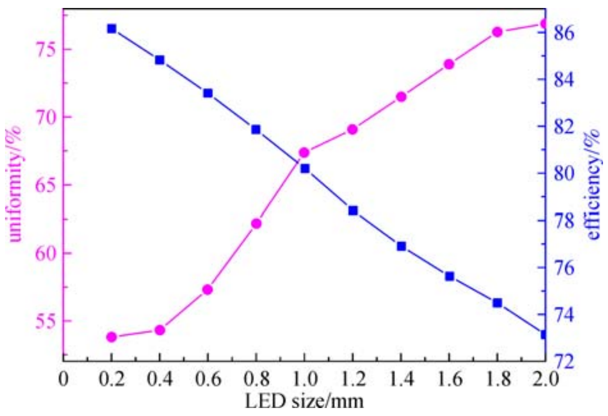


Fig. 10 Influence of LED chip size on the uniformity and the efficiency of the lens

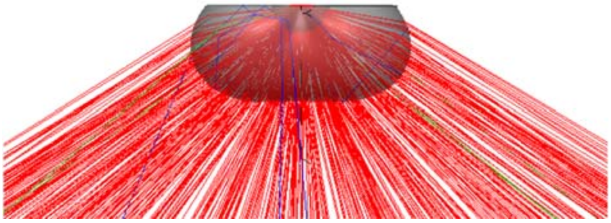


Fig. 11 Ray tracing of the freeform lens

ment. The number of freeform lenses can be increased or decreased according to the output luminous flux of the single freeform lens and the height of the road lamp installation. Here, an oval arrangement of lenses on the PCB was adopted, with the long axis length of the ellipse being 170 mm and a short axis length of 110 mm, as shown in Fig. 13. The B-B cross-sections of all lenses were in the direction of the road, and the A-A cross-sections of all lenses were in the direction vertical to the road. This oval arrangement was formed by a total of 136 freeform lenses in the same direction, which plays an important role in obtaining a compact structure with reduced volume.

The ray tracing and the photometric analysis of the road lamp were performed using the same conditions. Figure 14(a) shows the illuminance distribution; the shape of the illumination spot is still rectangular with a size of 40 m × 12 mm. The illuminance uniformity of the illumination area is 69.7% and the average illuminance is 24.6 lux. Figure 14(b) shows the polar candela intensity distribution curve. The light intensity of the far-field angle distribution is of the batwing type. The half-beam angle is 60° in the direction of the road and 30° in the direction vertical to the road. The results demonstrate that freeform lenses in an ordered arrangement cannot influence the shape of the illumination spot and can improve the average illuminance of the illumination area. This optical performance can fully satisfy the urban road lighting design standard.

Deviations in the horizontal (dH), vertical (dV), and tilt (dT) directions of the source usually occur during installation. In fact, the deviations of the freeform lenses on the PCB board cannot be the same. To analyze the misalignment and arrange the freeform lenses easily, we suppose that all freeform lenses have the same deviations to the PCB board. Additionally, we assume that the minimum tolerated uniformity is 60%, the average illuminance is 24 lux, and the minimum tolerated efficiency is 79.5%. Because rectangular illumination is not rotationally symmetric, we must analyze the dH and dT values of the LED position for cross-sections A-A and B-B. Figure 15(a) shows that for cross-section A-A, the efficiency decreases and the uniformity changes little with

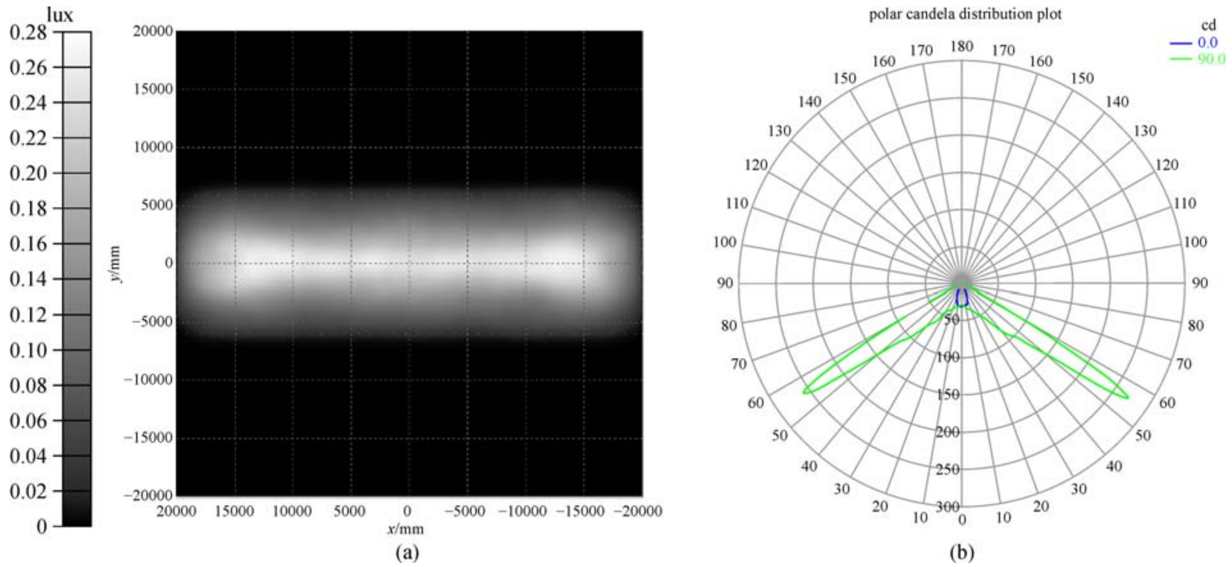


Fig. 12 Simulation of a single freeform lens. (a) Illuminance distribution at 12 m distance; (b) polar candela intensity distribution curve

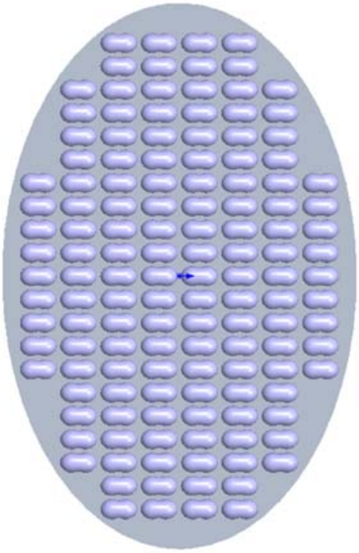
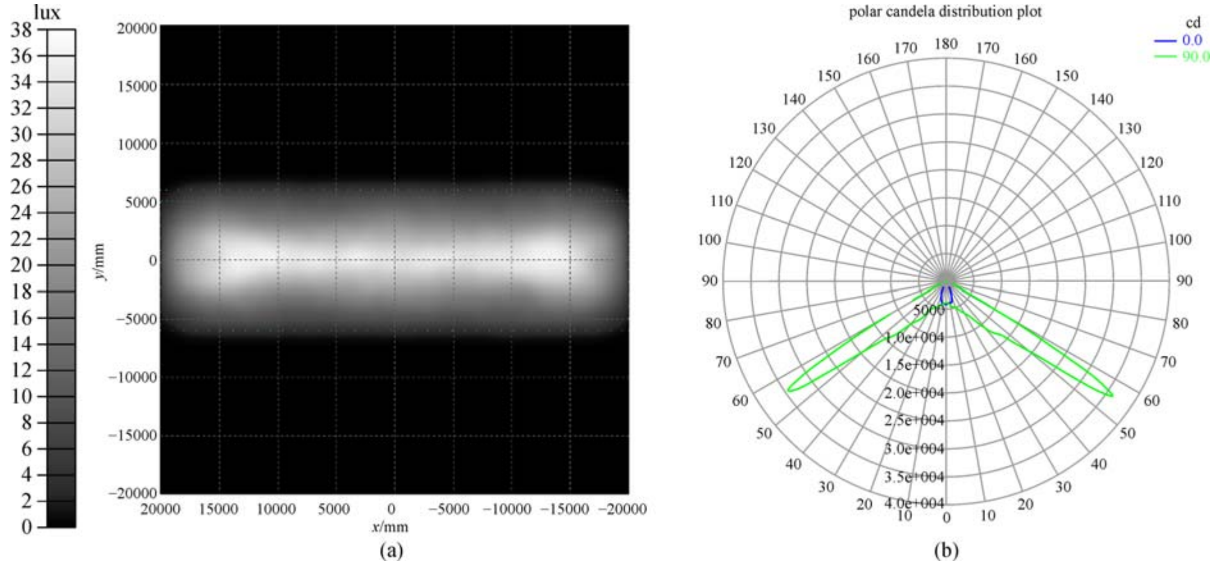


Fig. 13 Freeform lens arrangement on the PCB

increasing dH. The average illuminance exhibits a decreasing trend. In contrast, for cross-section B-B, the efficiency and the average illuminance are nearly invariable and the uniformity decreases from 67.4% to 54.3% with increasing dH, as depicted in Fig. 15(b). Figure 16 shows the vertical deviation of the LED. The uniformity decreases with increasing dV in the upward direction and increases with increasing dV in the downward direction. The efficiency increases with increasing dV and this increase is slower in the upward direction than in the downward direction. The average illuminance increases from 24.25 to 24.85 lux. As depicted in Fig. 17, the tilt deviation of the LED has little effect on the efficiency for both the A-A and B-B cross-sections. When dT increases from 0° to 5°, the uniformity variation decreases from 67.4% to 60.7% for cross-section A-A and from 67.4% to 66.2% for cross-section B-B. The efficiency and the average illuminance decrease with increasing dT and show the same trend as the uniformity. Therefore, the tolerance limits of the dH, dV, and dT deviations of the LED are -0.2 to 0.2 mm, -0.2 to 0.4 mm, and 3°, respectively. In the actual assembly process, the case of simultaneous dH, dV, and dT deviations must be also considered. After the simulation, we determined that the deviations of dV, dH, and dT were 0.2 mm, 0.2 mm, and 2°, respectively. The uniformity was 63.9%, the average illuminance was 24.5 lux, and the efficiency was 80.3%, which can fully satisfy the urban road lighting design standard.

4 Conclusion

A simple source–target luminous intensity mapping method is proposed to construct a freeform lens for rectangular illumination. First, the 2D contours of two mutually perpendicular cross-sections corresponding to the length and width of the rectangular illumination spot are calculated. Then, the initial points and maximum emission angles of other cross-sections are determined with geometric-optics analysis. The freeform lens can be constructed by using these counters as a framework and enveloping a layer of the smooth surface. Numerical simulations showed that the lighting performance of a single freeform lens is not sufficient for road lighting. Hence, an oval arrangement of freeform lenses on a PCB was adopted. When the installation height of the road lamp is 12 m, rectangular illumination with a size of 40 m × 12 m is obtained, the illuminance uniformity of the illumination area is 69.7%, and the average illuminance is



(a) (b)

Fig. 14 Simulation of road lamp. (a) Illuminance distribution at 12 m distance; (b) polar candela intensity distribution curve

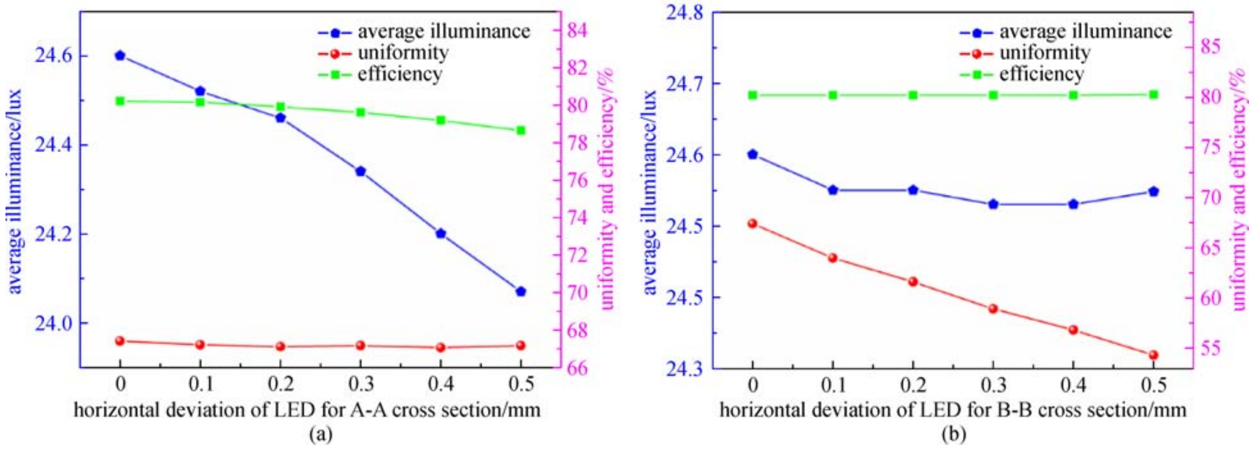


Fig. 15 Horizontal deviation of the LED for (a) cross-section A-A, and (b) cross-section B-B

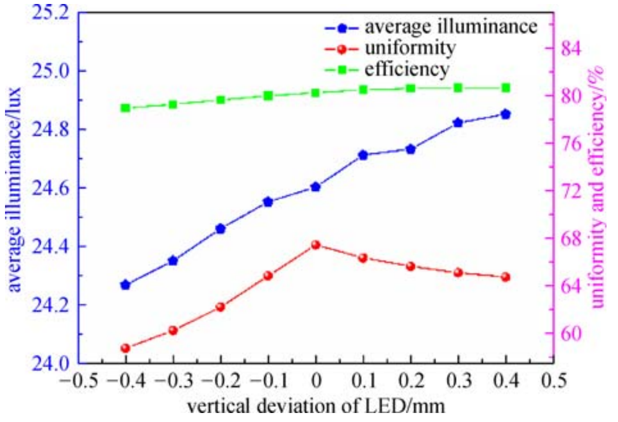


Fig. 16 Vertical deviation of the LED

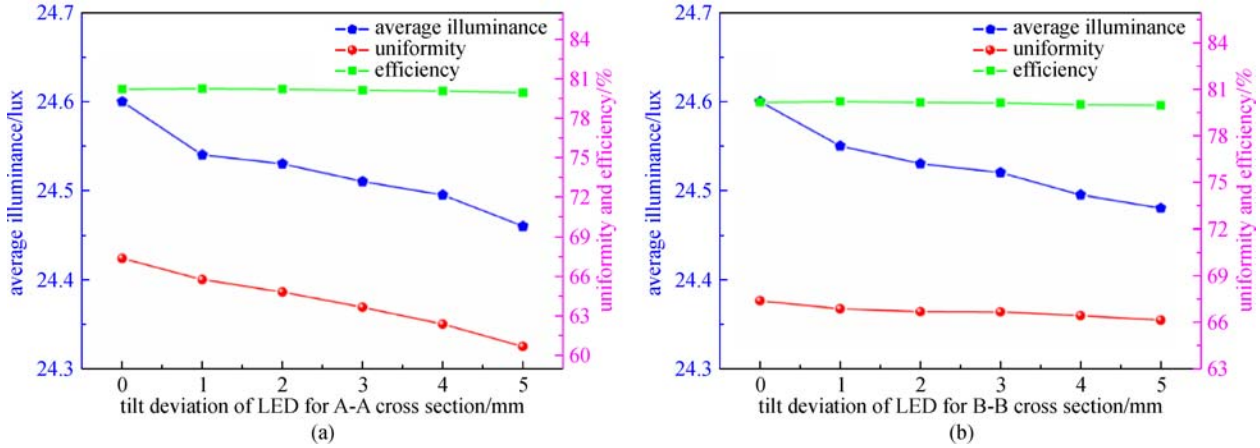


Fig. 17 Tilt deviation of the LED for (a) cross-section A-A, and (b) cross-section B-B

24.6 lux. The tolerance limits for manufacturing and installation errors were analyzed and their acceptable ranges are presented. The lighting performance can fully satisfy the urban road lighting design standard. This method may provide an effective way to design other freeform lenses with a LED source.

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