Optica Applicata, Vol. XLVIII, No. 3, 2018
10.5277/oa180307

Design of LED collimator for uniform illumination using two freeform lenses

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Regulating the illuminance distribution of an LED collimator to produce a uniform illumination in both the near field and the far field is a challenge in illumination design. In this paper, we present an effective method for designing two separated freeform lenses to control the illuminance distribution and the direction of the rays from the LED. The first lens redistributes the ray energy, and the second one collimates them to obtain a uniform collimated illumination. According to the conservation law of energy, Snell's law, Fermat's law and tangent-plane iterative method, the two freeform surfaces could be calculated simultaneously. The simulation results show that the two freeform lenses can control most of rays into an angle within ±1.5° for an LED with 1 × 1 mm size. The illuminance uniformities are higher than 0.9 in both the near field and the far field.

Keywords: illumination design, lenses, light-emitting diodes, optical design, high uniformity.

1. Introduction

Freeform surfaces are widely used in imaging systems [1–5] and non-imaging systems [6–11] with the advantages of high degree of freedom. A simple and effective method to define the shape of the freeform surface is to establish the partial differential equations (PDEs) and the data on the surface can be calculated numerically [12, 13]. Then the freeform surface is generated through surface fitting [14]. Simultaneous multiple surface (SMS) is a creative method to obtain two or more freeform surfaces simultaneously [4, 15]. The SMS method can solve more complex problems [4, 15–17].

A uniform collimated illumination for LEDs can be used in UV exposure illumination and LCoS projection display in the near field, and projection illumination in the far field. Although the design of the uniform illumination [6, 10, 11] and the collimated illumination [18, 19] for LED are very mature with one freeform surface, it is hard to obtain uniform illumination and collimated rays with only one freeform surface in the same time. In order to design an LED collimator for uniform illumination, MENG XIANG-XIANG *et al.* [20] calculate double freeform surfaces simultaneously based on the Malus law and the conservation of energy. The lens they obtain has two parts, one is the refracted composition in the center, another is the total internal reflected (TIR) composition on the side. Since each part has two freeform surfaces, they need to calculate the double freeform surfaces simultaneously twice. Besides, as the lens is spliced through the two parts together, the uniformity is poor at the splice. The simulation results show that there is a dark ring spot near the splice which affects the uniformity. CHEN CHEN and XIAOHUI ZHANG [21] collimate the rays first, and then redistribute the energy to obtain uniform collimated illumination for LEDs with two lenses. But the TIR structure is used in the collimator. The dark ring spot also appears near the splice. And the illuminance uniformity is not good enough.

In this paper, we present an effective method for designing two separate freeform lenses without TIR to gain a uniform collimated illumination for LEDs in both the near and the far field. There is no dark ring plot on the illuminated plane. And the illumination is with high and smooth uniformity. The first lens redistributes the light energy based on energy conservation, and the second one collimates the rays according to Snell's law and the tangent-plant iterative method. The two freeform surfaces are connected with Fermat's law and calculated simultaneously.

2. Design method

As shown in Fig. 1, the first lens we present here consists of a sphere and a freeform surface. The LED (regarded as a point source) is located at the center of the sphere.

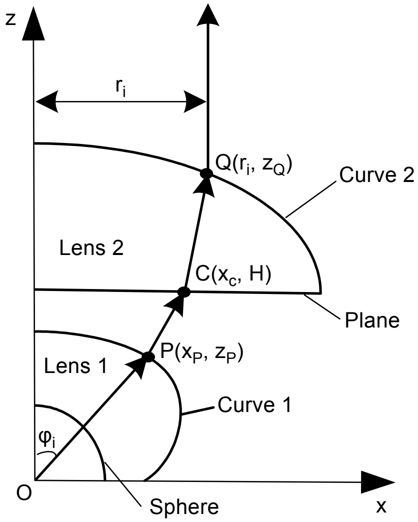

Fig. 1. The relationship of the points on curves 1 and 2.

So that the light from an LED shines into the lens without changing the direction. Then the light is refracted on the freeform surface. The incident surface of the second lens is a plane, and the exit surface is the second freeform surface, which collimates the light.

2.1. The relationship between the points on the two freeform surfaces

Supposing that the emitting half-angle of the LED is $\varphi_{\max}$ (usually $\varphi_{\max} = \pi/2$), and the radius of the collimator is R, according to the energy conservation, we have

$$2\pi\int_0^{\varphi_{\max}} I_0 \sin(\varphi)\cos(\varphi)\mathrm{d}\varphi = E_0 \pi R^2 \tag{1}$$

For arbitrary illuminated radius r_i $(0 \le r_i \le R)$, correspondingly there is an angle φ_i. Then we can get

$$2\pi\int_0^{\varphi_\mathrm{i}} I_0 \sin(\varphi)\cos(\varphi)\mathrm{d}\varphi = E_0 \pi r_\mathrm{i}^2 \tag{2}$$

From Eqs. (1) and (2), we can deduce that

$$r_\mathrm{i} = R\frac{\sin(\varphi_\mathrm{i})}{\sin(\varphi_{\max})} \tag{3}$$

Supposing that $Q(r_\mathrm{i}, z_\mathrm{Q})$ is a point on curve 2, and its corresponding point on curve 1 is $P(x_\mathrm{P}, z_\mathrm{P})$, the height of the refracted plane is H. Between the points $Q(r_\mathrm{i}, z_\mathrm{Q})$ and $P(x_\mathrm{P}, z_\mathrm{P})$, the refracted point on the plane is $C(x_\mathrm{c}, H)$. According to the geometric relation and Fermat's law, we get the relationship among points P, Q and C

$$\frac{(x_\mathrm{c} - x_\mathrm{P})^2}{(x_\mathrm{c} - x_\mathrm{P})^2 + (H - z_\mathrm{P})^2} = n^2 \frac{(r_\mathrm{i} - x_\mathrm{c})^2}{(r_\mathrm{i} - x_\mathrm{c})^2 + (z_\mathrm{Q} - H)^2} \tag{4}$$

where n is the refractive index of the lens material. In this design, the material of the optical entity is transparent plastic, Polycard (PC), with refractive index of 1.591. From Eq. (4), we can solve out the physical value of c_x. So that we can determine that the direction of outgoing ray on point P is $\mathbf{O}_\mathrm{P} = \overrightarrow{\mathrm{PC}}/|\overrightarrow{\mathrm{PC}}|$, and the direction of incident ray on point Q is $\mathbf{O}_\mathrm{Q} = \overrightarrow{\mathrm{CQ}}/|\overrightarrow{\mathrm{CQ}}|$. Obviously, the direction of outgoing ray on point Q is (0,1), and the direction of incident ray on point P is $(\sin(\varphi), \cos(\varphi))$. Then we can apply Snell's law to obtain the unit normal vector $\mathbf{N}_\mathrm{P}$ and $\mathbf{N}_\mathrm{Q}$ on point P and Q, respectively. And the tangent planes can be fixed by their unit normal vectors. The expression of Snell's law is

$$\mathbf{N} = \frac{\mathbf{O} - n \cdot \mathbf{I}}{|\mathbf{O} - n \cdot \mathbf{I}|} \tag{5}$$

2.2. Calculating the discrete points on the freeform curves

The points on the two freeform surfaces are calculated by Snell's law and the tangent -plane iterative method. The design of the two freeform profiles follows the following four steps.

Step 1. Choose an appropriate value for the initial points and parameters. As shown in Fig. 2, we set the height of the plane of the second lens at $H = 15$ mm and $R = 20$ mm. The initial points on the curve 1 and the curve 2 are $P_0(10\text{ mm}, 0)$ and $Q_0(30\text{ mm}, 0)$, respectively. So that $\varphi_0 = 0$ and $r_0 = 0$. Then the unit normal vector $\mathbf{N}_{\mathrm{P}_0}$ and $\mathbf{N}_{\mathrm{Q}_0}$ can be calculated using Eq. (5).

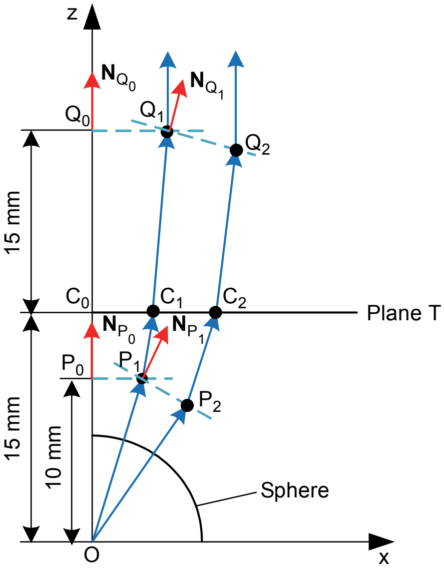

Fig. 2. Iterative method to generate the two freeform curves simultaneously.

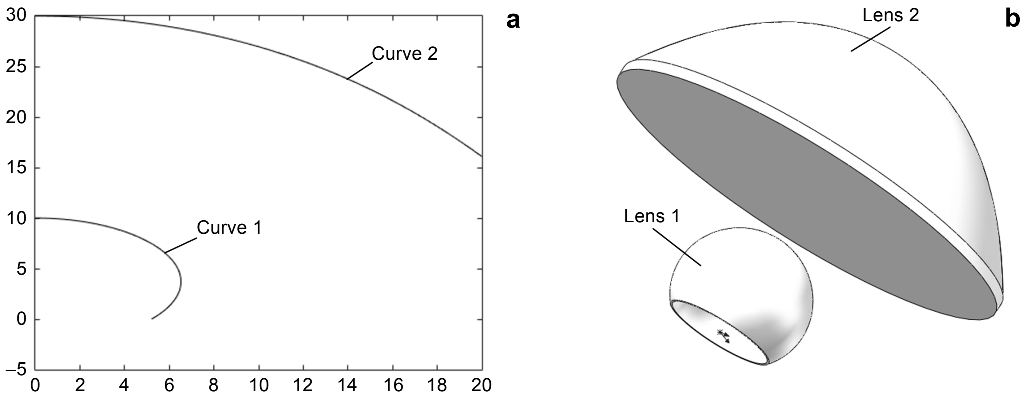

Fig. 3. The profiles of the two freeform surfaces (**a**), and the two lens entities by rotating the profiles (**b**).

Step 2. Calculate next new points on curve 1 and 2 simultaneously. Set a small value $\Delta\varphi$ (for example, $\Delta\varphi = \varphi_{\max}/1000$), then $\varphi_1 = \varphi_0 + \Delta\varphi$. And we can get r_1 from Eq. (3). According to the tangent-plane iterative method, the tangent plane crosses the next ray passing through the plane surface, getting the next calculation point. Then the next points $P_1(x_P, z_P)$ and $Q_1(r_1, z_Q)$ on curve 1 and 2 can be calculated.

Step 3. Calculate the unit normal vectors and obtain the tangent planes. When $P_1(x_P, z_P)$ and $Q_1(r_1, z_Q)$ are fixed, the corresponding refracted point $C(x_c, H)$ on plane T can be determined by Eq. (4). Then the incidence ray **I** and outgoing ray **O** on points P_1 and Q_1 are known from Section 2.1. Both the unit normal vectors on point P_1 and Q_1 can be calculated by Eq. (5). And the tangent planes are determined by unit normal vectors.

Step 4. Regard point $P_1(x_P, z_P)$ and $Q_1(r_1, z_Q)$ as initial points and repeat steps 2 and 3 until the calculation of φ_i is equal to $\varphi_{\max}$. Then the total data points on curve 1 and 2 are calculated.

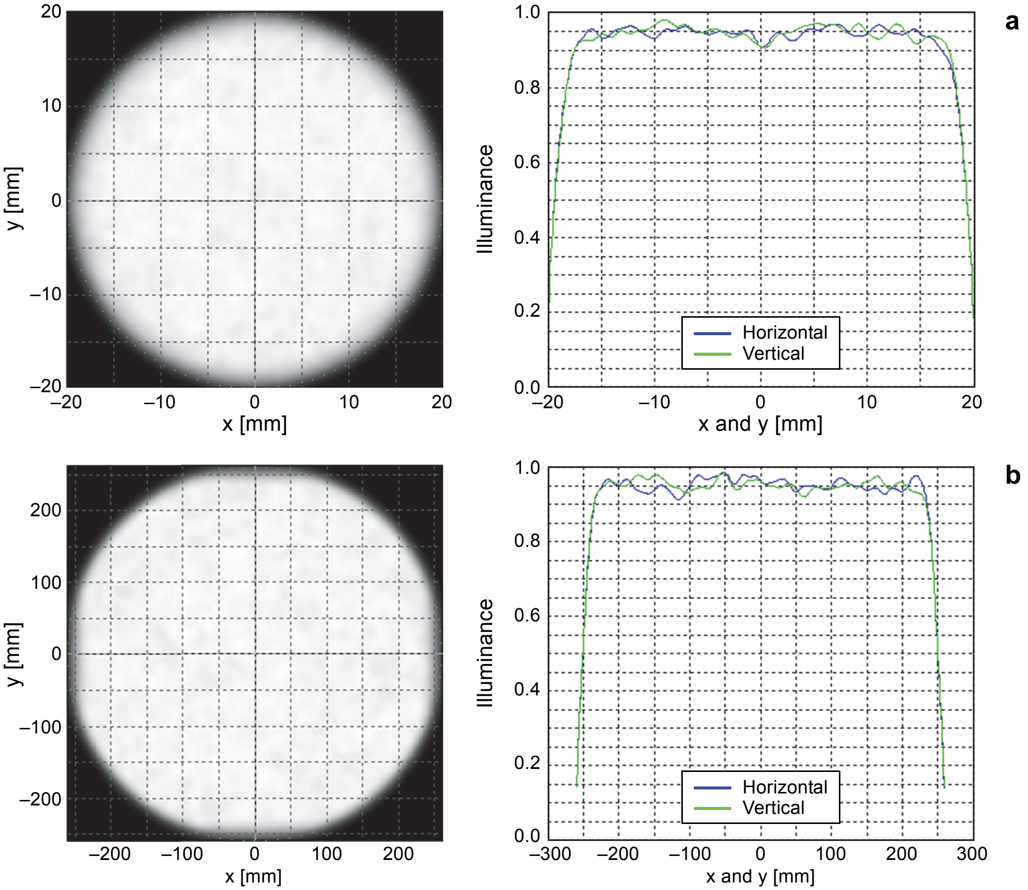

Fig. 4. Near field, $L_1 = 20$ mm (**a**), and far field, $L_2 = 10000$ mm (**b**) simulation results.

From the above steps, we calculate the profiles of the two freeform surfaces, which are shown in Fig. 3**a**. And Fig. 3**b** shows the two lens entities by rotating the profiles in SolidWorks.

3. Simulation results

In this section, we use the commercial optical software, TracePro, to simulate the optical system of the two lenses for a 1 × 1 mm size LED to study the illuminance uniformity. The number of the rays for the simulation is set to two millions. We simulate the illumination distance as $L_1 = 20$ mm and $L_2 = 10000$ mm, respectively. The results are shown in Fig. 4. From Fig. 4**b**, we notice that the radius of the spot on 10000 mm far plane is 260 mm, which indicates that the angle of divergence is 1.5°. It is worth noting that there is no dark ring plot on the illuminance plane, which affects the illuminance uniformity. Here, the illuminance uniformity is defined as [20]:

$$U = \left(1 - \frac{E_{\mathrm{max}} - E_{\mathrm{mean}}}{E_{\mathrm{mean}}}\right) \times 100\% \tag{6}$$

where E_{max} and E_{mean} are the maximum and average value of illumination in the target area, respectively. We can see from Fig. 4 that all the illuminance uniformity at these two illuminance distances is higher than 0.9 in central regions with a certain radius. The results indicate that the illuminance uniformities are high. However, since the two lenses have four interfaces, only 76% of total energy emitted from the LED source reaches the illuminated plane when considering the Fresnel loss.

4. Conclusions

According to the conservation law of energy, Snell's law, Fermat's law and tangent-plane iterative method, we present an effective method for designing two separate freeform lenses without TIR to gain a high uniform collimated illumination for LEDs on illuminated planes which are 20 and 10000 mm far away from the LED source, respectively, representing the near and the far field. The simulation results show that there is no dark ring plot on the illuminance plane comparing with the TIR lens. The two freeform lenses can control most of rays into an angle within 1.5° for 1 × 1 mm size LED. And the illuminance uniformities are both higher than 0.9 in the near and the far field. Ineluctably, since the two lenses have four interfaces, only 76% of total energy emitted from LED source reaches the illuminance plane considering the Fresnel loss. We will focus on how to improve the light efficiency in this method in the future work.

Acknowledgements – This work was supported by Natural Science Foundation of Guangdong Province (2016A030313473, 2015A030310278), Natural Science Foundation of China (6180030017), the Key

Technologies R&D Program of Guangdong Province (2016B090918057), the Key Technologies R&D Program of Guangzhou City (201704020038, 201704020182), Water Resource Science and Technology Innovation Project of Guangdong Province (2017-23), State Key Laboratory of Pulp and Paper Engineering (No. 201537), supported by Hunan Province Key Laboratory of Videometric and Vision Navigation.

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Received November 2, 2017
in revised form November 22, 2017