Optical design of adjustable light emitting diode for different lighting requirements*

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(Received 10 February 2012; revised manuscript received 9 May 2012)

Light emitting diode (LED) sources have been widely used for illumination. Optical design, especially freedom compact lens design is necessary to make LED sources applied in lighting industry, such as large-range interior lighting and small-range condensed lighting. For different lighting requirements, the size of target planes should be variable. In our paper we provide a method to design freedom lens according to the energy conservation law and Snell law through establishing energy mapping between the luminous flux emitted by a Lambertian LED source and a certain area of the target plane. The algorithm of our design can easily change the radius of each circular target plane, which makes the size of the target plane adjustable. Ray-tracing software Tracepro is used to validate the illuminance maps and polar-distribution maps. We design lenses for different sizes of target planes to meet specific lighting requirements.

Keywords: LED, optical design, freedom compact lens, energy mapping, adjustable, Tracepro

PACS: 71.55.Eq, 42.15.–i, 42.15.Eq **DOI:** 10.1088/1674-1056/21/12/127105

1. Introduction

A light emitting diode (LED) is a kind of good and efficient solid-state lighting source due to its long lifetime, high brightness, low price, and energy saving properties, which is widely used in today's lighting industry.[1−5] However, an LED source without any optical design cannot meet any requirement of the lighting industry, owing to its scattered and non-uniform lighting distribution (as shown in Fig. 1). In order to achieve a certain lighting distribution, optical design for LED sources is essential.

Freeform lens design is a kind of effective optical design,[6] however, traditional freeform lens design has the main disadvantage of large size, which raises difficulties in setting radiator. It leads the temperature inside the LED lamp to be unstable, which can shorten the lifetime of the LED source and shifts the colour index of the LED source. In addition, traditional freeform lens design is restricted by the dimension of the target plane:[7] each design might only meet one specific requirement.

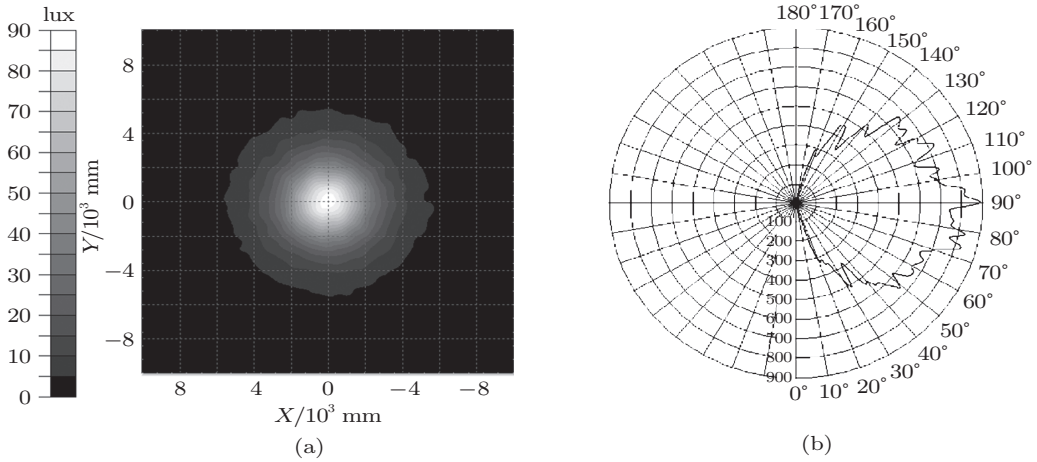


Fig. 1. Illuminance map (a) and light polar-distribution map (b) of LED source without optical design. The illumination of the target plane is scattered and non-uniform. This kind of lighting distribution cannot be used for special lighting requirements.

*Project supported by the State Key Development Program for Basic Research of China (Grant No. 2011CB013101).

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Once the dimension of the target plane changes, the optical design needs to be revised, which brings an extra cost on time and expenditure. To get rid of these limitations to traditional LED lens optical design, we propose a new practical optical design to meet the requirements of both large-range and small-range illumination. The freeform lens designed here has a smaller size than the traditional one and it could easily meet the requirement for different sizes of target plane. Furthermore, large-range uniform lighting distribution can be used in large-range interior lighting and small-range condensed lighting distribution can be used in flashlight design.

2. Establishing energy mapping[8−11]

Light distribution of an LED source follows Lambertian law: the light intensity of the LED source is $I(\theta) = I_0 \cos\theta$, where θ is the polar angle of the lighting source. In this paper, the minimum of θ is set to be 0 and the maximum of θ is assumed to be $\pi/3$, which is much closer to the value in a real situation. In order to obtain circular and uniform illuminance distribution, an energy mapping design is suggested.[6−9] We divide light energies from the LED source and the target plane into cells with the same number 100: first of all, we equally split the polar angle θ into 100 cells, $\theta_1 = 0$, θ_2, θ_3, ..., $\theta_{100} = \pi/3$, and $\Delta\theta = \theta_{i+1} - \theta_i = \pi/300$, the lighting energy E_i between two successive polar angles θ_i and θ_{i+1} is calculated, then we divide the target plane into a series of concentric circular areas, including 100 ring areas which are denoted as S_1, S_2, ..., S_{100}. The rule of splitting the target plane gives $S_i/S = E_i/E$, where S is the total area of the target plane and E is the total energy emitting from the LED source. As shown in Fig. 2, the energy mapping between the LED source and the target plane is established.

The compact freedom lens is designed according to Snell law, which could be stated as[10]

$$[1 + n^2 - 2n(\boldsymbol{O} \cdot \boldsymbol{I})]^{1/2}\boldsymbol{N} = \boldsymbol{O} - n\boldsymbol{I}. \quad (1)$$

Here $\boldsymbol{I}$ and $\boldsymbol{O}$ are the unit vectors of incident and refracted rays, $\boldsymbol{N}$ is the unit normal vector at the refracted point and n is the refraction index of the lens. Since the LED source and target plane are in axial symmetry, the lens design could be simplified in two-dimensional (2D) space. Figure 3 shows the geometric picture constructing the lens surface.

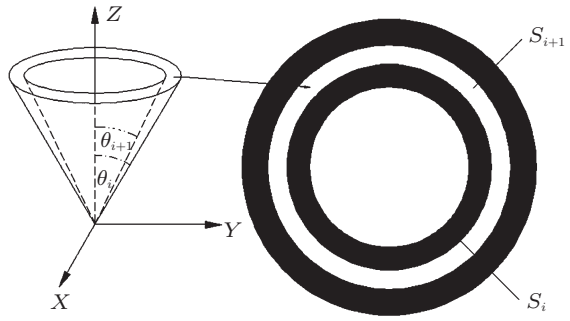


Fig. 2. Light energy mapping between the LED source and receiving surface: the illuminance between two successive polar angles corresponds to a certain ring area of the target plane.

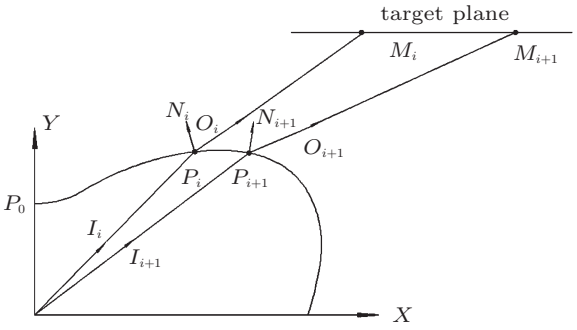


Fig. 3. Geometry of LED lens section.

As shown in Fig. 3, P_0 is the vertex of the lens, and the coordinate of P_0 could be set manually. Once P_0 is fixed, the first vector of incident ray $\boldsymbol{I}_1$ and the first refracted vector of ray $\boldsymbol{O}_1$ are known; then we could obtain the first unit normal vector $\boldsymbol{N}_1$ according to Snell law. With this algorithm, we could obtain the light at each of the points on the lens section. With the lens section calculated, the entire lens model is constructed by computer aided design (CAD) software.

3. Modeling and ray-tracing

After the lens model is established, we come to validate the lighting distribution of the target plane with ray-tracing software. Tracepro (Lambda Research Corporation, Littleton, MA) is a commercial software based on Monte Carlo ray-tracing method, which is used in our simulation.

In this paper, two lens models are calculated with the algorithm mentioned above. For large-range interior lighting, such as factories and big shopping mall lighting, a wide range circular target plane with high uniformity light distribution is needed. The radius of the circular target plane is set to be 5 m, and the

height of the lens is set to be 10 mm. We select a kind of glass named BK7 as the material for the lens. Its refraction index is 1.51. In this model, the distance between the LED source and target plane is set to be 3 m. The lens model calculated in this situation is shown in Fig. 4.

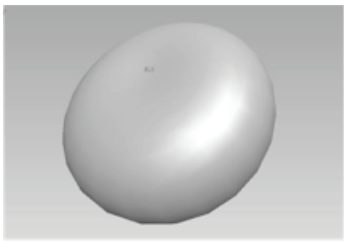
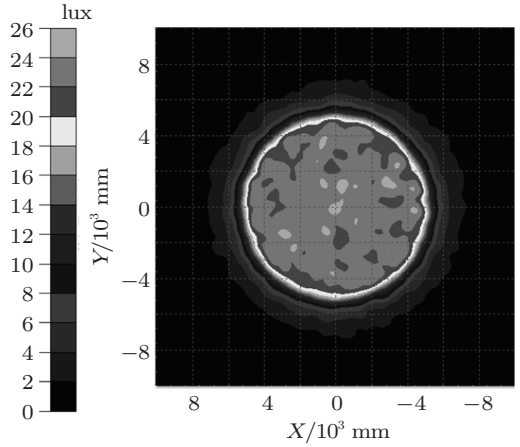
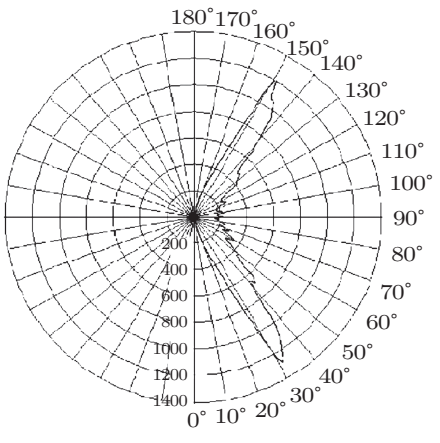


Fig. 4. Lens model calculated by CAD software in large-range uniform design.

In Tracepro software, an optical system is established to validate the lighting distribution of the lens as shown in Fig. 4. We trace 10^5 rays emitted from the LED source and obtain the lighting distribution as shown in Fig. 5. From it we can see the lighting distribution of this design is a circular area whose radius is close to 5 m and the uniformity of the circular target plane is over 80%. The polar-distribution map shows that the ray-emitted angle concentrates on 30° and 150° as compared with that in Fig. 1(b) in which the polar-distribution has no optical design.



(a)



(b)

Fig. 5. Illuminance map (a) and polar-distribution map (b) of LED source with large-range uniform optical design.

For small-range condensed lighting design, such as flashlight design, we confine the ray from the LED source in a small circular area whose radius is less than 1 m. In this model, the distance between the LED source and target plane is set to be 3 m, and the height of the lens is set to be 10 mm. The material of the lens is also selected to be BK7. Figure 6 shows the model that is constructed using CAD software in small-range condensed optical design. Figure 7 shows the illuminance map and polar-distribution map of this small-range condensed optical design. From Fig. 7(a) we can see that the lighting distribution in this design is a circular area whose radius is close to 1 m and the uniformity of the target plane is also over 80%. Figure 7(b) shows that the ray-emitting angle is restricted in a range from 70° to 110°. This design effectively confines the light into a small range. As a result, our design can be applied to small-range lighting distribution, especially to flashlight design.

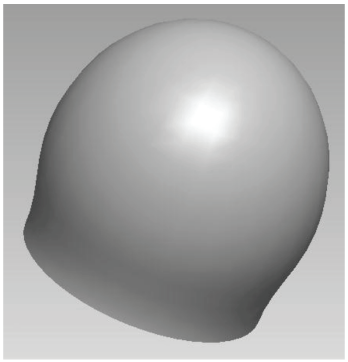
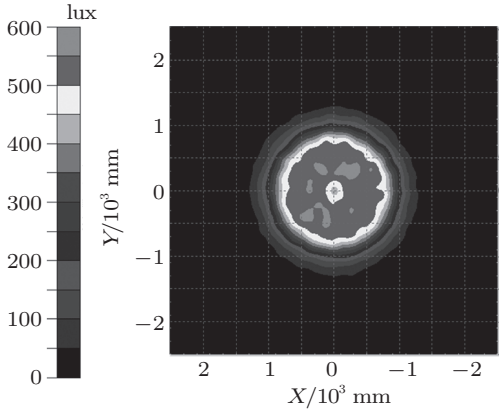
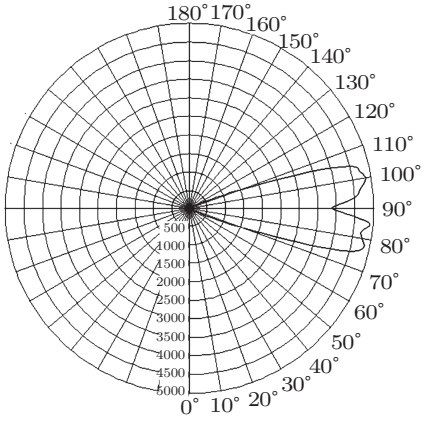


Fig. 6. Lens model calculated by CAD software in small-range condensed optical design.



(a)



(b)

Fig. 7. Illuminance map (a) and polar-distribution map (b) of LED source with small-range condensed optical design.

4. Conclusion

In this paper, we proposed an optical design to meet different lighting requirements. Our algorithm is based on the energy conservation law and Snell law. Through adjusting the radii of circular target planes, highly uniform circular lighting distributions with different radii are simulated. This design can be applied to both large-range interior lighting and small-range condensed lighting.

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