Design of a novel LED collimating element based on freeform surface*

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A novel element for collimating LED light is designed based on non-imaging optics. It is composed of a refraction lens and a reflector. The upper surface of the lens is freeform and calculated by geometrical optics and iterative process. The lens makes the rays in the range of 0°−45° from the optical axis collimated. The rays in the range of 45°−90° from the optical axis are collimated by the reflector. The inner surface of the reflector is parabolic with its focus located in the LED chip. The designed element is applicable to LED source of any emitting type. For a certain application, the simulation results of the designed element in Tracepro show that it has a very compact structure and good collimating performance. Just investigating the loss in the lens surfaces, this element has high light output efficiency of nearly 99%. Most lighting area radii are no more than 20 mm when the illuminated plane is 5 m away from the LED source.

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High power white LEDs have begun to play an important role in many illumination systems due to their excellent performance, such as small volume, high light output efficiency and long lifetime. However, for some specific application situation, such as searchlights, spotlights, flashlights and night-vision systems, the emitted rays from the LEDs need to be collimated. The secondary optical design for LEDs is essential to these applications[1]. It belongs to the category of non-imaging optics, and can be divided into the design for point source and the design for extended source[2,3]. For point source, when illumination distribution pattern is given, it can be abstracted into a mathematical model. But for extended source, there are many considerable issues. A typical design method for the extended source is simultaneous multiple surface (SMS) method[4]. Non-imaging optical design aims for higher efficiency of the lights and more rational distribution of the luminous intensity. The types of the designed elements always are reflective, refractive or composite of them[5,6]. The surfaces used in these elements are sphere, asphere or freeform surfaces[7]. Nowadays, freeform surface becomes a prevalent in the secondary optical design for LEDs. H. Ries and J. A. Muschaweck[8,9] introduced the tailoring method to solve the freeform surface. In recent years, many internal researchers in Tsinghua University, Zhejiang University and Huazhong University of Science and Technology have had success with the design of freeform surface elements for LED lighting systems[10,11].

In this paper, a novel LED collimating element is designed based on geometry optics and non-imaging optics theory. It is composed of a freeform surface lens and a parabolic reflector. The freeform surface of the lens is calculated by the tailoring method. This designed element is applicable to LED sources of any emitting type. Numerical simulation results demonstrate that the novel collimating element has high light output efficiency of more than 99% and good collimating performance. It makes that the LED source can be directly used in spacific lighting systems.

To avoid the total reflection of the rays with large emitting angles, the rays emitted from the LED chip are collimated by a freeform surface lens and a parabolic reflector,

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respectively. The structure of the novel LED collimating element is shown in Fig.1. Fig.2 shows the side-glance of it.

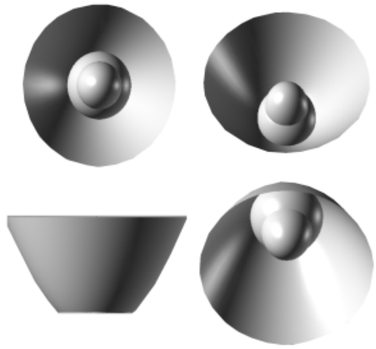


Fig.1 Model of the novel collimating element

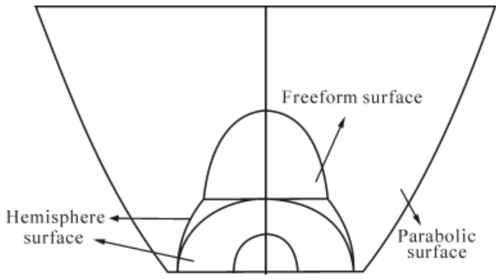


Fig.2 Side-glance of the novel element

There is a hemisphere surface in the bottom of the lens, and the LED chip locates in the center of it. The surface of the lens has two parts. The upper part of the lens' surface is freeform, which is calculated by tailoring method. The angle between the optical axis and the boundary of the freeform surface is 45°, so that the rays in the range of 0°−45° from the optical axis are collimated by the freeform surface. The lower part of the lens' surface is another hemisphere surface which is concentric with the smaller one. The rays in the range of 45°−90° from the optical axis can not be refracted by this surface. The bottom radius of the reflection cup is a little larger than the radius of the lens' bottom. The upper radius of the cup is equal to the height of it, and the inner surface of the reflection cup is parabolic surface with its focus point located in the LED chip. So that the rays in the range of 45°− 90° from the optical axis can be collimated by this cup. Moreover, to limit the element's volume, the bottom radius of the cup should be nearly equal to that of the lens. Therefore, all the rays emitted from the LED chip are collimated by this novel element.

The calculation method of the freeform surface of the lens can be illustrated as follows. Because the distribution of the LED luminous intensity is rotationally symmetric, the design can be simplified into two-dimensional coordinates[12]. We just need to obtain a freeform curve as a freeform surface generatrix, which can be rotated by 360° around the optical axis to get the corresponding freeform surface.

For a point source and considering the case of refraction, as shown in Fig.3, if the freeform surface and the target plane are divided into grids with equal number and the grids are corresponding to each other, there is only one incident ray at each grid node on the freeform surface. According to the edge-ray theorem, the ray at the node of each grid on the freeform surface corresponds to a point on the target plane. The rays within any two grid nodes on the freeform surface can be injected into the area between the two corresponding points on the target plane[13]. Then for a given radius of the collimated light in a certain area, we just need to divide the radius of the target and the freeform surface into corresponding equal grids. The vector of each refracted ray can be controlled by the normal vector at each grid of the incident ray. This progress is implemented by solving the first-order partial differential equation based on Snell law. If the number of the divided grids is large enough, all the rays incident to the whole freeform surface can be collimated.

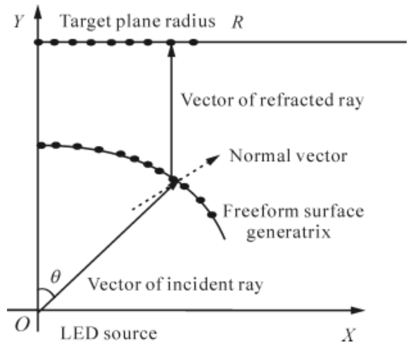


Fig.3 Corresponding relationship between the freeform surface generatrix and the target plane

In the case of two-dimensional coordinates, there are three steps to solve the freeform surface generatrix. Firstly, divide the radius of the collimating area at the target plane into N points. When the freeform surface covers half spatial distribution of the rays from LED chip, the radius of the target plane should be $R/2$ if the collimating plot radius is R. Then the radius R_i of the ith point on the target plane can be expressed as

$$R_i = \frac{R}{2N} \cdot i \,,\ i = 0, 1, 2, \cdots, N \,. \tag{1}$$

Secondly, divide the rays in the range of 0°−45° from the optical axis into N parts along the angle θ. To make sure each ray can be injected into the corresponding point on the target plane, the ith angle θ_i of the ith ray can be expressed as

$$\theta_{i+1} = \theta_i + \arctan \frac{\Delta R}{\rho_i} \,,\ i = 0, 1, 2, \cdots, N, \tag{2}$$

where θ_i is the angle between the ith ray and the optical axis Y, $\Delta R=R12N$, and ρ_i is the radius vector of the ith ray.

Lastly, as shown in Fig.4, according to the tailoring method, the freeform surface generatrix is divided into N grids by the incident rays with the angle θ_i (i = 1, 2,⋯, N). The normal vector of any grid is $\boldsymbol{N}$, the unit vector of the incident ray at this grid is $\boldsymbol{In}$, and the unit vector of the refracted ray is $\boldsymbol{Out}$. Based on the Snell law, they satisfy the equation as

$$[1+n^2-2n(\boldsymbol{Out}\cdot\boldsymbol{In})]^{1/2}\cdot\boldsymbol{N}=\boldsymbol{Out}-n\cdot\boldsymbol{In}\ , \quad (3)$$

where n is the relative index. For the designed lens and the refraction surface, n should be the relative index between air and the material of the lens. Choose an initial point S_0 on the freeform surface generatrix, whose corresponding point on the target is the target center T_0. The unit vector of the incident ray at this point $\boldsymbol{In_0}$ could be calculated by (0, ρ_0), and the unit vector of the refracted ray $\boldsymbol{Out_0}$ could be calculated by (x_0-$\rho_0\sin\theta_0$, y_0-$\rho_0\cos\theta_0$). Then the normal vector $\boldsymbol{N_0}$ at this point can be obtained by solving Eq.(3), and the equation of the tangent at this point is obtained, too. The second point S_1 on the freeform surface generatrix is calculated by the intersection of the incident ray $\boldsymbol{IN_1}$ and the tangent of the previous point. The direction vector of the refracted ray $\boldsymbol{OUT_1}$ can be also obtained as T_1S_1, where T_1 is the corresponding point of incident ray $\boldsymbol{IN_1}$ on the target plane. Then we can obtain the normal vector $\boldsymbol{N_1}$ of the second point according to Eq.(3). And the equation of the tangent at this point is obtained, too. The third point S_2 is the intersection point of the incident ray $\boldsymbol{IN_2}$ and the tangent. Based on this algorithm, we can obtain all other points and their normal vectors on the freeform surface generatrix. Thus, the point coordinates on the freeform surface generatrix are ascertained. The generatrix can be rotated around the Z axis with 360° to form the freeform surface.

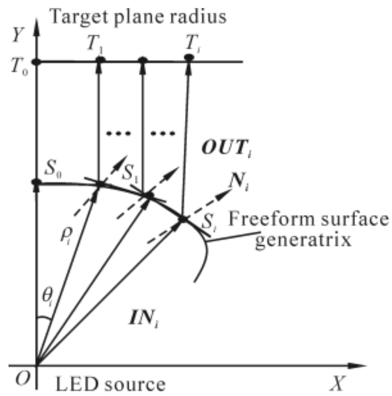
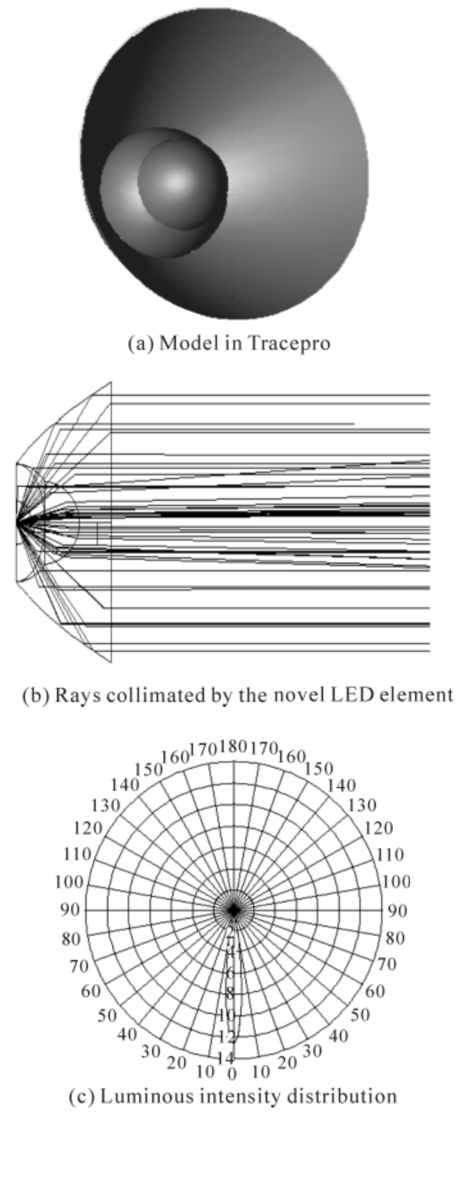
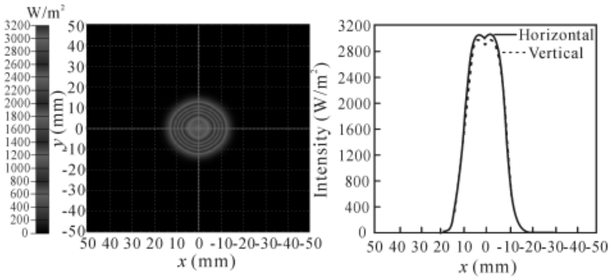


Fig.4 Schematic diagram of the method to solve the freeform surface generatrix

A collimating element as an LED package to achieve a lighting area with 20 mm diameter at 5 m away is designed to demonstrate the validity of this method. The refractive index of the material (as PMMA) is 1.49. The bottom diameter of the reflector cup is 8 mm, and the upper diameter of it is 20 mm. The model of the designed element is shown in Fig.5(a). An LED chip with the size of 1 mm × 1 mm is established, the relative position of each part is constituted in Tracepro, and 1000 rays from the LED chip are traced. The simulation results of the collimating element are shown in Fig.5(b) and (c). The diameter of collimated spot is about 20 mm at the target plane 5 m far away from the LED source, which is extremely consistent with the expected results. All the half-space rays emitted by the LED chip are collimated. The number of the rays received by the target surface is 990. The light output efficiency is defined as the ratio of the number of the rays incident in the target plane to that emitted from the LED source without considering the lens material transmission, so the efficiency of the designed element is about 99%.

For collimating the rays from the LED lighting source, a





(d) Illumination distribution of the target plane

Fig.5 Simulation results of the designed LED collimating element

novel LED collimating element is designed. The method for solving the freeform surface of the collimating lens is introduced in detail. Compared with other numerical solution methods, the proposed method is simpler, faster, and does not need optimization. For a specific instance, the simulation results prove that the design method is correct, and the structure of this novel element is logical. It makes the LED lighting source be more widely applied in the lighting situations.

References

[1] YAN Xing-tao, YANG Jian-feng, BU Fan and ZHANG Guo-qi, A Novel LED Lens for Rotationally Symmetric Uniform Illumination, IEEE International Conference on Electronics and Optoelectronics **3**, 82 (2011).

[2] ZHOU Long-zao, LIU Hui, AN Bing, WU Feng-shun and WU Yi-ping, Journal of Optoelectronics • Laser **21**, 175 (2010). (in Chinese)

[3] Roland Winston, Juan C. Minano and Pablo Benitez, Nonimaging Optics, Burlington: Elsevier Academic Press, 2005.

[4] P. Benítez, J. C. Miñano, J. Blen, R. Mohedano, J. Chaves, O. Dross, M. Hernández and W. Falicoff, Opt. Engineering **43**, 1489 (2004).

[5] SHI Ling-na, PAN Ying-jin and DONG Guang-xian, Journal of Optoelectronics • Laser **21**, 1133 (2010). (in Chinese)

[6] YAN Xing-tao, YANG Jian-feng and ZHANG Guo-qi, Infrared and Laser Engineering **41**, 718 (2012). (in Chinese)

[7] J.-J. Chen and C.-T. Lin, Opt. Engineering **49**, 093001 (2010).

[8] H. Ries and J. A. Muschaweck, Tailoring Freedom Lenses for Illumination, Proc. of SPIE **4442**, 43 (2001).

[9] H. Ries and J. A. Muschaweck, J. Opt. Soc. Am. A **19**, 590 (2002).

[10] DING Yi, ZHENG Zhen-rong and GU Pei-fu, Opt. Express **16**, 12958 (2008).

[11] WANG Kai, LIU Sheng, CHEN Fei, QIN Zong, LIU Zongyuan and LUO Xiao-bing, J. Opt. A: Pure Appl. Opt. **11**, 105501 (2009).

[12] WANG Hong, WANG Hai-hong, ZHANG Xiao-fan and ZHANG Qi-hui, Journal of Optoelectronics • Laser **21**, 1163 (2010). (in Chinese)

[13] JIANG Jinbo, Sandy To and W. B. Lee, China Illuminating Engineering Journal **19**, 59 (2008). (in Chinese)