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New structure of side-collimating lens for LED with high collimating performance based on geometrical optics

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Abstract **Original Research Article**

In order to improve collimating performance, we proposed a new structure of side-collimating lens. The lens surfaces are evaluated based on purely geometric optics. We used a point source for theoretical model, but used a LED chip with a size of 1 mm × 1 mm in all simulations. The ray diverged from the LED chip is collimated perpendicular to the optic axis of LED after refracting or total internal reflecting by the lens. Since the ray is collimated laterally by the lens, we have considered collimating performance in conjunction with a reflector. Effects of initial conditions on the size and collimating performance of the lens were analyzed. Simulation results show that the light flux percentage is achieved 95.23% under a half view angle of ±2° for a LED chip. Most illuminating area (dominating 80% light flux) radii are no more than 3 m when the target surface is 100 m apart from LED. These simulation results manifest that the lens has good collimating performance and its new structure is a valuable.

Keywords: Collimating Lens, Geometrical Optics, Collimating Performance.

1. Introduction

In recent years, LEDs have been using widely in varied illumination systems because of their excellent performances, such as energy saving, low heat, high luminous efficiency, long life, environmental conservation and small volume. However, the radiation pattern of LED chips themselves doesn't meet the illumination requirements in various circumstances. So, it is essential to design optic elements such as lenses, reflectors to attain desired illumination. In the past decade, many methods for designing the illuminating lens have been proposed [1-5]. Source–target energy mapping method [6-10] is mainly used to give uniform illumination light on the target plane. Numerical solution method [11-14], solving differential equations of freeform surface data, which are formulated by Snell's law and the equal principle of optical path, depends largely on the initial conditions, and it's difficult to calculate. SMS design method [15,16] can effectively establish the iterative relationship between neighboring sampling points through the numerical relationship, and procure the discrete point data of the freeform surface. Compared with other methods, the SMS method is not only suitable for designing freeform surface lenses of point sources, but also has good design effect for various types of extended sources. In addition, this method can be used to optimize the direction of the emitted rays, thus achieving ideal design results.

Today, the LED collimating lens has a wide range of applications. For some specific illumination systems, such as aviation obstruction lights, marine beacons, spotlights and searchlights, it is essential to collimate the rays diverged from the LEDs. Wang *et al*. [17] proposed two kinds of collimating lenses that collimate the LED light beam founded on non-imaging optics theory and geometrical optics. This proposal has the advantage of fast design without requiring optimization and iterative processing. Wang *et al*. [18] designed a collimating lens with a small size and good optical efficiency by constructing a freeform surface based on a construction access and a simple geometrical optics analysis. Chen *et al*. [19] proposed a collimating lens with high optical efficiency by lowering Fresnel losses at refracted surfaces based on Snell's law and Fresnel's equation. Kumar *et al*. [20] proposed a novel freeform lens that collimates ultraviolet radiation diverged from ultraviolet LEDs founded on geometric optics. Qiao *et al*. [21] presented a method for designing a collimating lens with high accuracy by generating the lens profile based on aberration theory. This method shows a foundation for tool of designing collimating lenses. So far, traditional collimating lenses have been some differences in design methods, however, in most cases, structurally, the front light beam of the LED is collimated by refraction and the side light beam by total internal reflection(TIR). It is possible that the front beam of the LED is collimated by TIR, resulting in a higher collimation performance than that collimated by refraction.

The goal of the present research is to create a structure that can improve the collimating performance and to find the design parameters to achieve a small lens size and high collimation performance. Unlike traditional lenses, we propose a lens that collimates the front light beam of the LED by TIR and the side light beam of the LED by refraction. The lens is designed founded on purely geometric optics. The proposed design method has the advantage that the method is a simple and the design time is a short, since lens surfaces can be expressed by the equation. Depending on the initial conditions, lenses of different sizes and performances can be obtained. We construct an optical system consisting of the lens and a reflector so that the lateral collimated beam is parallel to the optic axis of LED. This optical system can be used in illuminating environments that require high light intensity and narrow divergence angle. We will hereafter refer to the traditional collimating lenses-which organize rays diverged from an LED chip into collimated beam having a direction parallel to an optic axis of the LED, as the front-collimating lenses.

2. Design Method

In this paper, considering that the collimating performance by reflection is higher than collimating one by refraction, we researched a new structure of side-collimating lens. The side-collimating lens organize light diverged from an LED chip into collimated beam having a direction perpendicular to an optic axis of the LED. Fig. 1 shows a 2D section view of the side-collimating lens. The section view is symmetric with respect to the optic axis of LED (*y*-axis). The 3D model of the lens is a 360-degree rotation of half of this section view around the optic axis of the LED. The side-collimating lens is constructed of a TIR element, which suits front beam (e.g., ray1 and ray2 in Fig. 1), and a refractive element suiting the side beam (e.g., ray3 in Fig. 1). In Fig. 1, the TIR element consists of a parabolic surface, a spherical surface and a cylindrical surface, and the refractive element consists of an aspheric surface and a cylindrical surface.

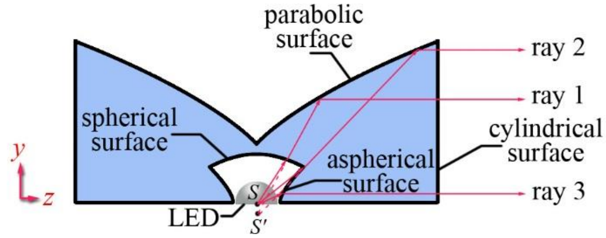

Fig. 1. 2D section view of the side-collimating lens.

The design of side-collimating lens can be divided into the designs of TIR and refraction elements. Fig. 2 shows a schematic diagram for the design of a refractive element. The first surface of a refractive element is aspheric, the second is cylindrical. The location of LED *S* is the front focus of the refractive element. A front focal length *f* equals *SE*. *n* is the rendering index of the lens.

In Fig. 2, according to the principle of equal optic path, the optic length of rays between united points is same. that is

$$SB+n\cdot BC= SE+n\cdot ED$$

transforming the above expression, it can be written as:

$$SB+n\cdot BC=f+n(z-f+BC)$$

hence

$$SB=f+n(z-f)$$

where $SB=\sqrt{y^2+z^2}$. We get the equation of the hyperbolic curve after transformation:

$$y^2=(n^2-1)z^2-2f\cdot n(n-1)z+(n-1)^2 f^2 \tag{1}$$

This equation can be converted to the following hyperbolic equation:

$$\frac{(z-z_m)^2}{a^2}-\frac{y^2}{b^2}=1 \tag{2}$$

where $a=\dfrac{f}{n+1}, b=\sqrt{\dfrac{n-1}{n+1}}f, z_m=\dfrac{n}{n+1}f$.

Thus, the main parameters determining the shape of the hyperbola, *a*, *b* and z_m, are calculated by the distance *f* from the LED chip *S* to the vertex *E* of the hyperbola and the refractive index *n* of the lens.

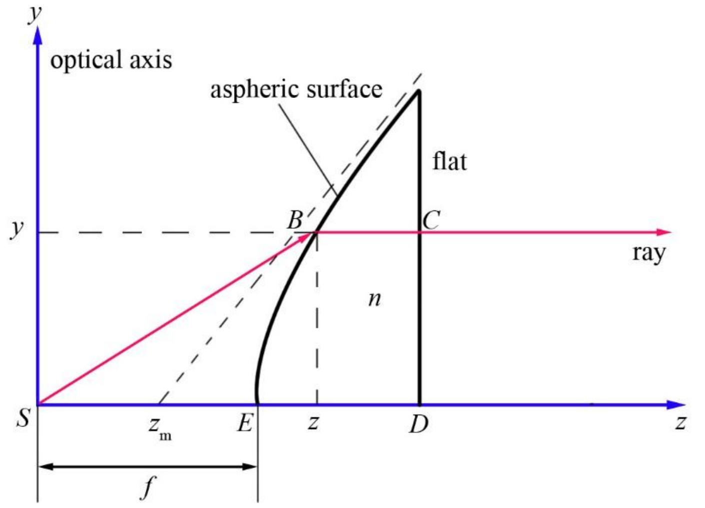

Fig. 2. Illustrational diagram for the design of the refractive element.

Fig. 3 shows an illustrational diagram for the design of a TIR element. If the center point *O* of the spherical surface coincides with the position *S* of the LED, the refraction does not occur in the spherical surface, so that the collimating performance of the lens becomes high, but the overall size of the lens becomes large. Aiming to decrease the overall size of the lens, we determined the radius and center position of the spherical surface so that the image point S' of S lies below S. R is the radius of spherical surface.

In the concave lens (e.g., spherical surface in Fig. 3), we have:

$$\frac{n}{S'A} - \frac{1}{SA} = \frac{n-1}{R}$$

$$S'A = \frac{n}{1+\frac{1}{k}(n-1)}h \quad (3)$$

where $k=R/h$, h is the distance from the LED to the vertex of the spherical surface.

Hence, the equation of the circle, which is a two-dimensional contour of the spherical surface, can be obtained as follows:

$$z^2 + (y+R-h)^2 = R^2 \quad (4)$$

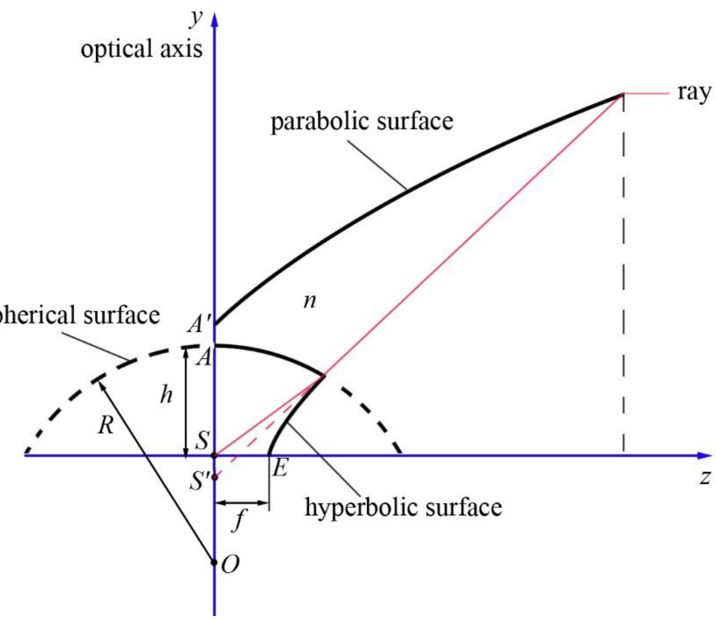

Fig. 3. Illustrational diagram for the design of the TIR element.

The focus of the parabolic surface coincides with S'. In this case, the equation of the parabola, which is a 2D contour of a parabolic surface, is

$$z = \frac{(y+S'A-h)^2}{2p} - \frac{p}{2} \quad (5)$$

where $p=S'A+AA'$.

3. Simulation and Analysis

In 3D modeling software *SolidWorks*, first, 2D contour of the lens is sketched based on Eqs. (2) -(5), then it is rotated to obtain a 3D model. 3D model is imported to optical simulation software *LightTools* for simulation. Fig. 4 shows the optical system combined of a side-collimating lens and a reflector. The size of LED chip used for the simulation was 1 mm × 1 mm, the luminous flux from the LED was 100 lm, the wavelength was 550 nm, and the light intensity pattern was Lambertian type. In the simulation, the reflectance of the reflector is 100 %, and the scattering and absorption losses are 0%. The target surface is 100 m away from an LED chip and the number of rays traced in simulation are 1 000 000. The lens material is PMMA (n = 1.49) and *AA´* is taken as 1 mm considering the fabrication.

Fig. 5 indicates the ratio of the maximum illuminance (maxE) to the lens exit diameter (*W*) versus the *k* value for a lens with *f* = 2.5 mm and *h* = 5 mm. The maximum of the four values is 100%, and the residual values are expressed as relative values with respect to the maximum. This figure shows that the collimating performance is higher when *k* = 2, if the lens size is the same. Fig. 6 is an intensity line chart for a lens with *f*=3.5 mm and *h*=7mm(*k*=2).

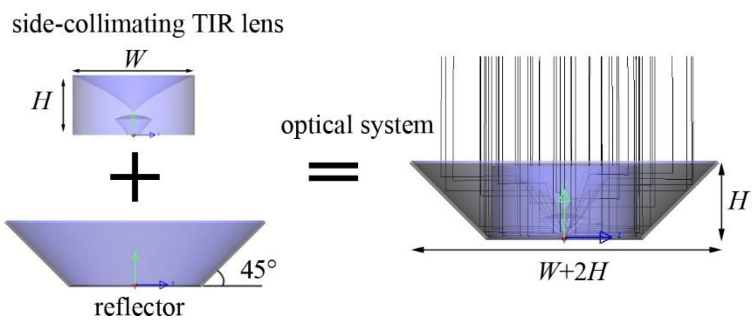

Fig. 4. Optical system combined of a side-collimating lens and a reflector.

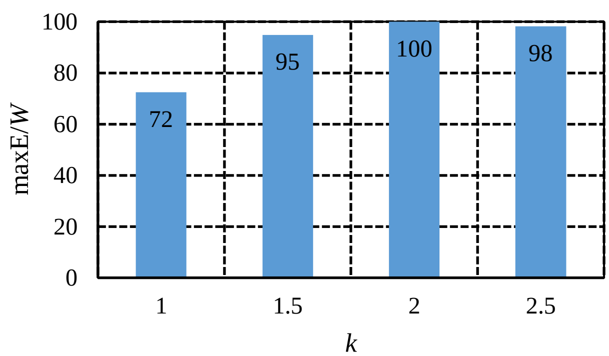

Fig. 5. maxE/*W* versus *k* for a lens with *f* = 2.5 mm and *h* = 5 mm.

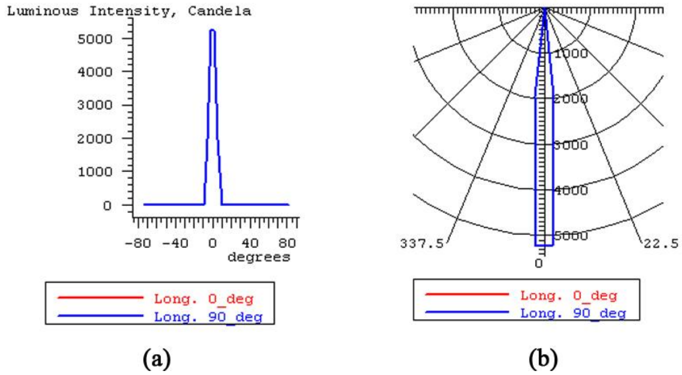

Fig. 6. Light intensity line chart.

Fig. 6(a) and Fig. 6(b) are intensity line charts over cross-sections for 0° and 90° along longitudes in Cartesian and polar coordinate, respectively. For this lens, figs. 7(c) and 7(d) show the illuminance raster chart and dimensions, respectively. Figs. 7(a) and 7(b) are illuminance raster charts for lenses with (a) f=2.5 mm, h=5 mm, and (b) f=3 mm, h=6 mm, respectively. For the same k value, the larger f and h are, the larger maximum illuminance on the target surface is. For the same k value, this means that a lens with bigger values of f and h has a better collimating performance. Figs. 8(a), 8(b), and 8(c) are the surface charts of illuminance for lenses with (a) f=3.5 mm, h=5 mm; (b) f=3.5 mm, h=6 mm; and (c) f=3.5 mm, h=7 mm, respectively.

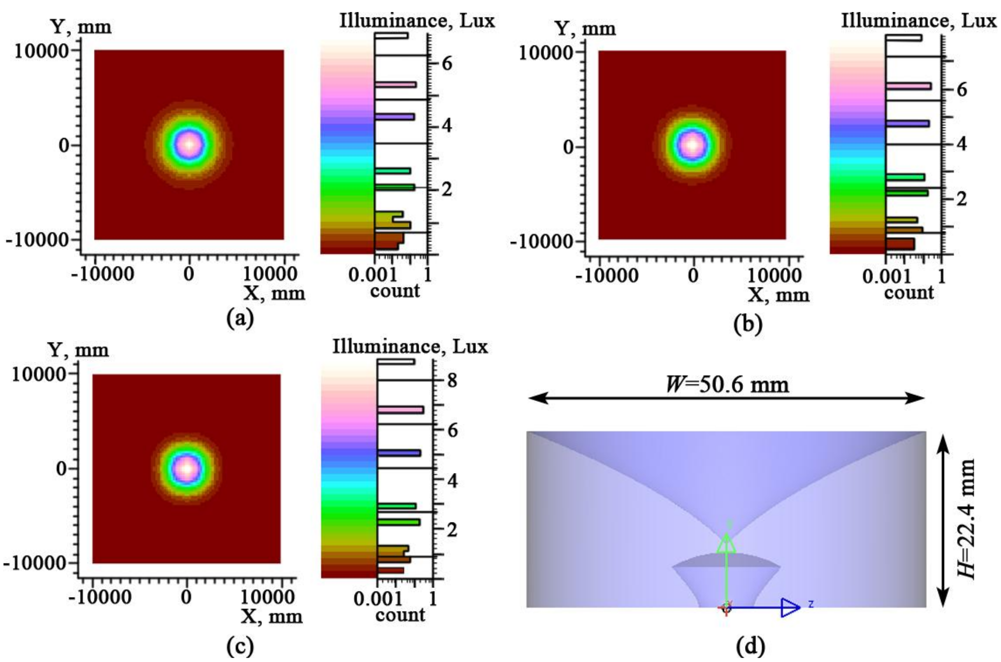

Fig. 7. Illuminance raster charts and dimensions of lenses with k=2.

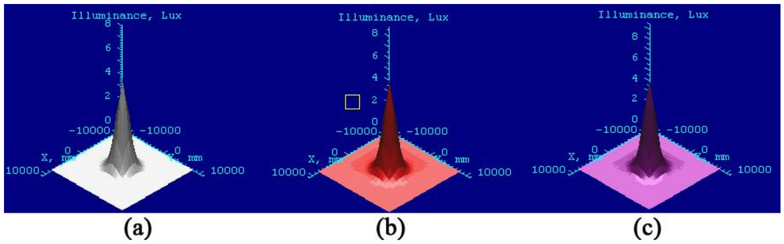

Fig. 8. Surface charts of illuminance for lenses with (a) f=3.5 mm, h=5 mm; (b) f=3.5 mm, h=6 mm; and (c) f=3.5 mm, h=7 mm.

To estimate the collimating performance quantitatively, we investigated the area that involves 80% flux of all the light flux in the target surface. If the distance from LED chip to target surface is 100 m, the radius of the area shows collimating performance. Fig. 9 shows the flux percentage versus light spot radius, for the same simulation conditions, for lenses with different sizes.

Fig. 9 indicates, for the same k value, lens with larger f and h has a better collimating performance. Efficiency (eff) and light spot radius of lens with f=3.5 mm and h=7 mm is 99.9% and 2.2 m, respectively. Where, efficiency means the ratio of the flux in the target surface to the flux from LED chip. When f=3.5 mm and h=5 mm, the light spot radius is 2.6 m and the efficiency is 99.89%.

The light flux percentage versus half view angle is shown in Fig. 10. The light flux percentage of lens with f=3.5 mm and h=7 mm is achieved 95.23% within a half view angle of ±2°. This result manifests that this lens has good collimating performance for an LED source.

It is very valuable to investigate the effect of initial conditions (f, h and k) on the collimating performance and lens size. Fig. 11 shows the results. In Fig. 11, the maximum of values of each parameter is 100% and the residual values are shown as the relative amount to the maximum.

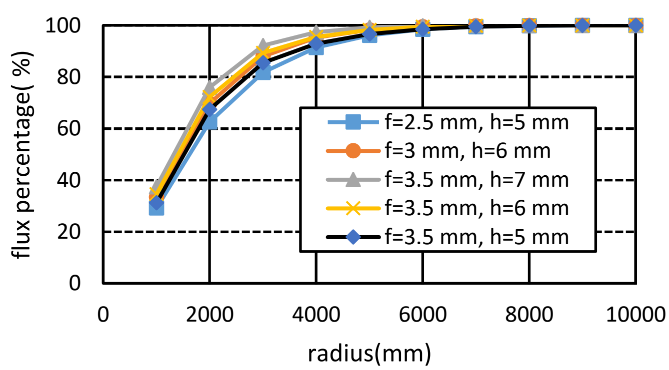

Fig. 9. Flux percentage versus light spot radius.

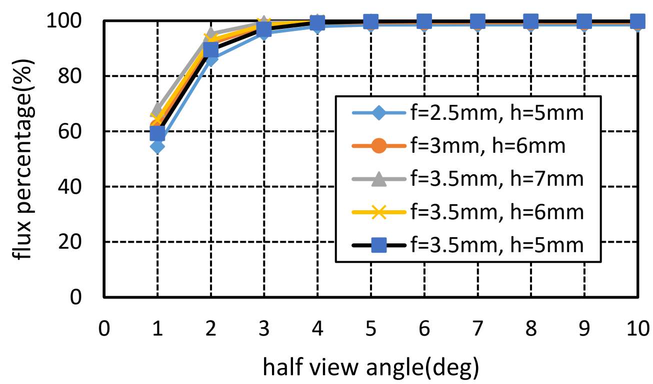

Fig. 10. flux percentage versus half view angle.

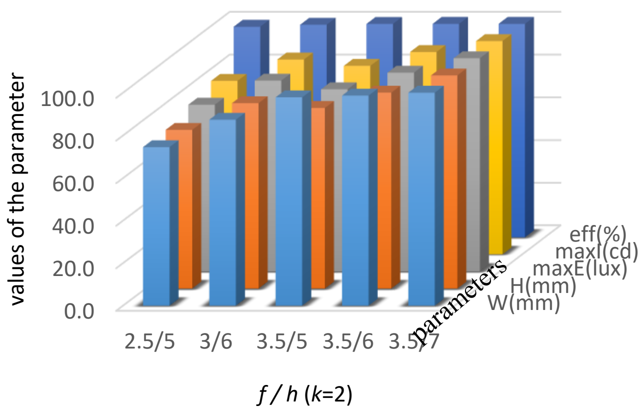

Fig. 11. Impact of initial condition on the lens.

In Fig. 11, the term "*H*" means to the maximum height of lens and the term "*W*" refers the lens exit diameter. It can be seen that the efficiencies of all the lenses are larger than 98% and are almost unchange d. From Fig. 11, for the same *k* value, a lens with bigger values of *f* and *h* has bigger lens diameter and height.

4. Conclusion

We designed a simple and fast side-collimating lens based on only geometric optics. This method was not dependent on the complicated numerical analysis method as compared to the traditional design methods. It is particularly effective for LEDs with high-density light beam in the paraxial axis direction. The designed lens has the disadvantage of requiring additional optical element (reflector), but it has the advantage of small size, high collimating performance, high efficiency, and simple design. The design process consists of mathematical modeling for 2D contours of the lens, constructing 3D model and optical simulating. This lens can be used in illuminating systems that require high light intensity and narrow divergence angle, such as marine beacon, aviation obstruction light, searchlight etc.

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