Design Method of Secondary Optical Element for LED Applications

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ABSTRACT

Light Emitting Diode, LED, has many advantages in many lighting applications, such as general illumination, street light, and auto lamp. In general, each application needs to do secondary optical design for its specific request. A secondary optical element can be separated into refractive and reflective part. In this paper, we present a design procedure of secondary optical design with intensity distribution of LED and sequential ray tracing. The method suits the both designs of refractive and reflective parts. In the first process, we integrate the series function of intensity distribution in spherical coordinate with a range of solid angle. In the second process, we calculate the redistribution parameters of luminous flux by the geometric parameters of LED, element, and detector. In the final process, we use ray tracing method to design the optical element by aspheric surface. The surface of the refractive part in secondary optical element could be Fresnel surface for reducing the thickness of element. For proving the design procedure, we design a secondary optical element of LED by this method with an illumination request.

Key words: LED Applications, Secondary Optical Design, Fresnel Lens, Aspheric Coefficients, Optimization,

1 INTRODUCTION

Light Emitting Diode, LED, has many advantages in many lighting applications, such as general illumination, street light, and auto lamp. In general, each application needs to do secondary optical design for its specific request [1, 2]. A secondary optical element can be separated into refractive and reflective part. In this paper, we present a design procedure of secondary optical design with intensity distribution of LED and sequential ray tracing. In the first process, we integrate

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the series function of intensity distribution in spherical coordinate with a range of solid angle. In the second process, we calculate the redistribution parameters of luminous flux by the geometric parameters of LED, element, and detector. In the final process, we use ray tracing method to design the optical element by aspheric surface. The surface of the refractive part in secondary optical element could be Fresnel surface for reducing the thickness of element. For proving the design procedure, we design a secondary optical element of LED by this method with an illumination request.

2 DESIGN METHOD

In the applications of the LEDs, we always need to do secondary optical design to fit the requests. The secondary optical element could be separated into reflective and refractive element. The reflective element may be a reflector that bases on elliptic or parabolic curve to offer a focusing or parallel beam. The refractive element may be a lens. We would like to offer a design method about how to design a secondary optical element. In this paper, we use a Fresnel lens with aspheric coefficients to be the example that is thinner and powerful to control the light.

2.1 System Structure

According to the system concept, any engineering problem could be separated into input, system, and output, as shown in the Fig. 1. In an optical system, the input is always light sources such as sunlight, arc lamp, LED, and CCFL; the system is made up of reflective and refractive elements; and the output may be human eye or detector. In this paper, we assume the input is a LED array, the system is a Fresnel lens with aspheric coefficients, and the output is a screen, as shown in the Fig. 1.

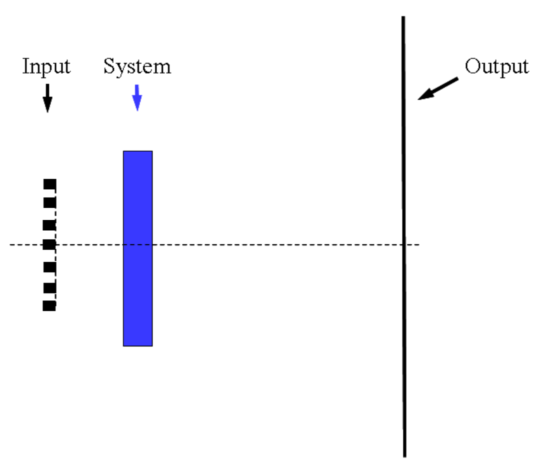

Fig. 1 The illustration of the system structure in a secondary optical design

About the input, either single LED or LED array should be considered as a plane source because the distance between the light source and the secondary optical element is shorter than 10 times of the dimension of LED. It means we should replace the far field radiation of LED by the near field when we to the secondary optical design. Although the near field radiation must be measured for the accuracy, we can simplify the near field by considering the light source is made up of point sources whose view angle is same to the LED.

About the system, the slopes of each ring in the Fresnel lens will decide the refractive angle of each beam. It means we can redistribute the radiation of LED by control the slops of Fresnel lens. For high freedom to design the slops, we use the aspheric polynomial to design the secondary optical lens. The standard polynomial is a series, as shown in the Eq. 1. In this function, the optical axis of the Fresnel lens is Z axis and the lens lies on the X-Y plane; the cv is the curvature and cc is the conic constant of the surface; and the r^2 is x^2+y^2 and the a_1 to a_n are aspheric coefficients .

$$Z=\frac{cv\times r^2}{1+\sqrt{1-cv^2\times(cc+1)\times r^2}}+a_1\times r^2+a_2\times r^4+a_3\times r^6+a_4\times r^8+a_5\times r^{10}+\dots \tag{1}$$

About the output, we always evaluate the efficiency of the LED system by the distribution of intensity and illumination. The unit of intensity is cd, lumen per solid angle, that describes energy of a point source, and the unit of illumination is lux, lumen per meter square, that describes energy of an illuminated surface. In an application of LED, the illumination of the screen is determined by the intensity of the LED system includes LED and secondary optical elements. We assume the goal of the example in this paper is uniform distribution of illumination.

2.2 Design Conditions

We assume the design conditions that include the light source and the secondary optical lens in the Fig. 2. In the input, the LED array is made up of 25 LEDs, and the radius of the array is 19.5 mm. The distribution of intensity is lambertian whose characteristic is the luminance of light source is independent of angle. According to the distance, 10 mm, between the LED array and Fresnel lens, the controllable range of the Fresnel lens is ± 30° in edge point of the LED array. Therefore, we only design the secondary optical lens to redistribute the intensity inside ± 30° and leave other intensity with reflector. In the system, the radius of the Fresnel lens is 25.5 mm, the distance between the lens and the screen is 150 mm, and the target size is 175.5 mm. According to the conditions, the view angle of the LED system is 45°.

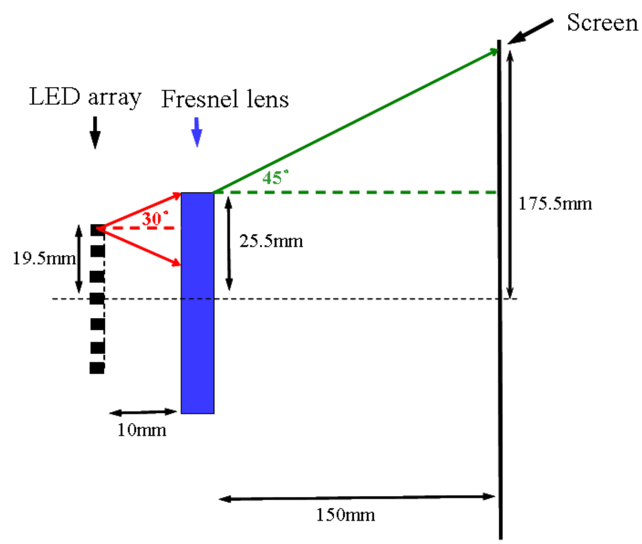

Fig. 2 The design condition of the secondary optical design

2.3 Design Procedure

In the design method, we will separate the intensity distribution into several pieces by angle ranges in which there has the same total energy to each other. If we can control each piece of energy to illuminate difference areas on the target whose sizes are the same, the average illuminations of the all areas are the same. When we separate the intensity into more pieces, the illumination on the target is more uniform.

In the example, we divide the target into three areas, as shown in the Fig. 3. Because the size of each area is the same, we use the Eq. 2 to calculate the radii, a and b. The r is 175.5 mm, so the a is 101.325 mm and the b is 143.295 mm.

$$\pi \times a^2 = \pi \times \left(b^2 - a^2\right) = \pi \times \left(r^2 - b^2\right) = \frac{1}{3} \times \pi \times r^2 \tag{2}$$

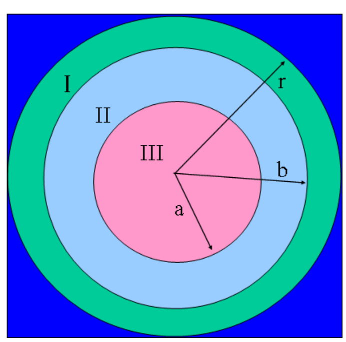

Fig. 3 The illustration of the divided target

After calculated the radii of the three areas on the target, we can divide the intensity distribution of the LED system that is in the image space of the Fresnel lens into three pieces, as shown in the Fig. 4. The energy inside the blue line will illuminate the area III on the target, the energy between blue and red lines will illuminate the area II on the target, and the energy between red and green lines will illuminate the area I on the target. If the three energies are the same, the average illuminations on the three areas are also the same. Because optical system is a linear system, the three pieces on the image space of the Fresnel lens should correspond with the object space of the secondary optical lens.

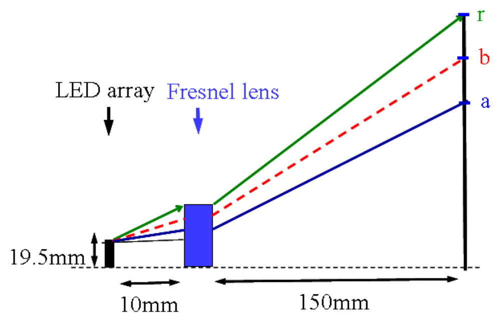

Fig. 4 The illustration of the divided intensity

Because the input, LED array, is not smaller than the 0.05 times of the Fresnel lens, the light source in the secondary optical design is considered as a plane source not a point source. It means we should use the near field radiation of LEDs to design the secondary optical lens. In this paper, we suppose the LED array is made up of point sources to fit the condition so the separation of the intensity distribution is by angle ranges. As shown in the Fig. 5, the intensity on the image space is divided into three pieces by θ_1, θ_2, and θ_3 for each point source. Because the total energy of each piece is the same, we use the Eq. 3 to calculate the angles, θ_1, θ_2, and θ_3, in which the $I(\theta)$ is $\cos\theta$. The θ_3 is 30°, so the θ_1 is 16.779° and the θ_2 is 24.095°.

$$\int_0^{\theta_1}\int_0^{2\pi} I(\theta)\times\sin\theta\, d\varphi\, d\theta = \int_{\theta_1}^{\theta_2}\int_0^{2\pi} I(\theta)\times\sin\theta\, d\varphi\, d\theta = \int_{\theta_2}^{\theta_3}\int_0^{2\pi} I(\theta)\times\sin\theta\, d\varphi\, d\theta = \frac{1}{3}\times\int_0^{\theta_3}\int_0^{2\pi} I(\theta)\times\sin\theta\, d\varphi\, d\theta \qquad (3)$$

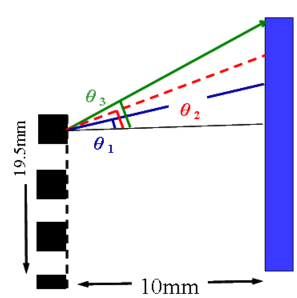

Fig. 5 The illustration of the divided intensity on the object space of the Fresnel lens

3 OPTICAL SIMULATION

After the evaluation and calculation, we use a sequential ray tracing software to design and optimize the Fresnel lens with aspheric coefficients. And then, we use a non-sequential ray tracing software to simulate the illumination on the screen.

3.1 Optimization

According to the parameters from the design procedure, the rays from all points of the LED array should hit the outside edge of the area I when the included angles between optical axis and the rays are 30°; the rays should hit the outside edge of the area II when the included angles are 24.095°; and the rays should hit the outside edge of the area III when the included angles are 16.779°. For simplifying the optimization, we only consider the rays when the ray tracing plane includes the optical axis.

In the optimization, we set the pupil mode to be telecentric; the two surfaces of the lens to be Fresnel surfaces; aspheric coefficients of two surfaces to be variables; and the request conditions to be operands. The layout of the optimized optical system is shown in the Fig. 6. Because we only set the conditions of the rays to be operands when the ray will hit the up half of the target, the ray distribution is not good on the other half.

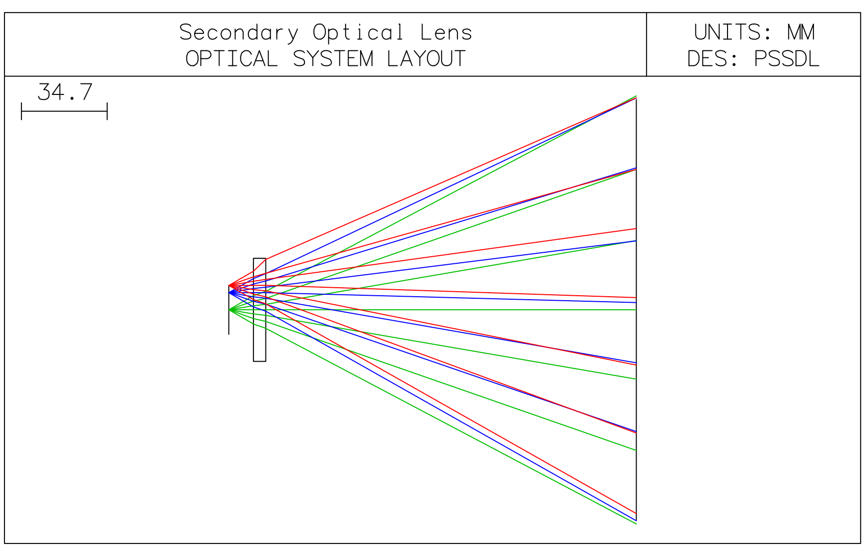

Fig. 6 The optical system layout after optimization on sequential ray tracing software

3.2 Result

According to the parameters of the Fresnel lens, we build a 3D model with the Acryl material in the non-sequential ray tracing software, as shown in Fig. 7. The squares are LEDs and the disk is the Fresnel lens. In this simulation, the view angle of the LEDs is 40° that is the same condition when we design the lens. We assume the intensity out of the 40° will be control by a reflector which will be design in future with same method.

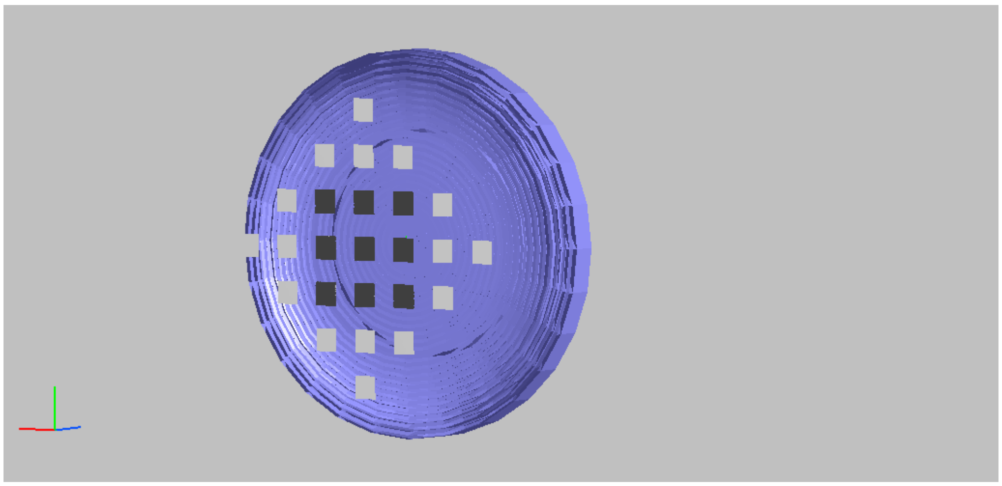

Fig. 7 The optical system layout after optimization on non-sequential ray tracing software

The Fig. 8 shows the simulation results that include a simulation without secondary optical lens and a simulation with the Fresnel lens. The efficiency of the LED system with the lens is 97 % that is more than the efficiency of the LED system without lens, 80 %. However, the definitions of the operands base on ideal condition of the rays, so the uniformity is not better.

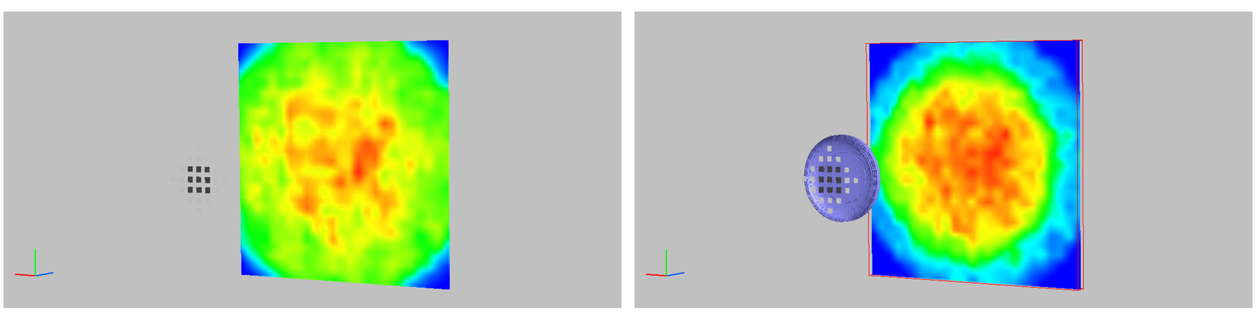

Fig. 8 The simulation results with (left) and without (right) the Fresnel lens

4 CONCLUSION

In this paper, we offer a design method about how to design the secondary optical element in the LED application. First, we divide the intensity distribution of LEDs into several pieces by angle ranges in which there has the same total energy to each other. Second, we control each piece of energy to illuminate difference areas on the target whose sizes are the same. If we separate the intensity into more pieces, the illumination on the target is more uniform. For example, we design a Fresnel lens with aspheric coefficients to redistribute the intensity of LED array. Because we use ideal conditions of the rays to define the operands when we optimize the Fresnel lens, the uniformity is not good. In this example, we only control the view angle and efficiency. In the future, we will redesign the Fresnel lens with the complete operands, design a reflector to control the intensity out of the 40°, fabricate the element, and measure the performance of the manufactured lens to prove this method.

REFERENCE

[1] Whang, A. J. W., Li, P. C., Chen, Y. Y., and Hsieh, S. L., "Guiding light from LED array via tapered light pipe for illumination systems design," Journal of Display Technology, 5(3),104-108 (2009).

[2] Whang, A. J. W., Chen, Y. Y., and Teng, Y. T., "Designing uniform illumination systems by surface-tailored lens and configurations of LED arrays," Journal of Display Technology, 5(3), 94-103 (2009)