

## Original research article

## A new optimization method of freeform surface lens based on non-imaging optics for led source



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## ABSTRACT

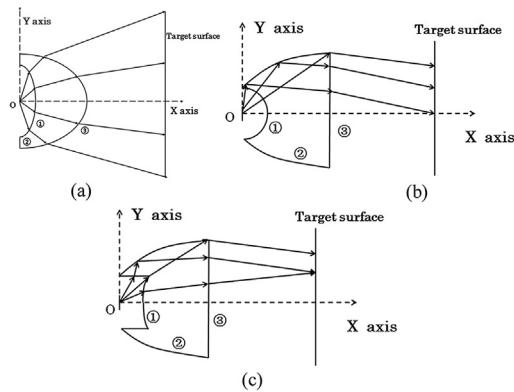
An optimization method in the design of freeform surface lens based on non-imaging optics to achieve uniform illumination for LED source is proposed. In this design, regular quadratic curve is used as the initial model, and the Scheme programming language and the optimization engine in the TracePro software are used in combination to achieve the control and optimization of local freeform curve. A Lambert emission of 1mm × 1 mm LED is used as simulation source. Three kinds of freeform surface lenses are investigated. It is shown that the uniformity is respectively 97%, 96% and 95% within the field of view of ±14°, ±30° and ±12° at the target surface 1 m away from the source. The energy efficiency is respectively 80.9%, 86.7% and 89.2% for the three lenses. Compared with current traditional optimization methods, the illumination uniformity and energy efficiency are improved significantly. It also possesses advantages of simplicity in process, less reliability on initial model, less optimization time, and good versatility.

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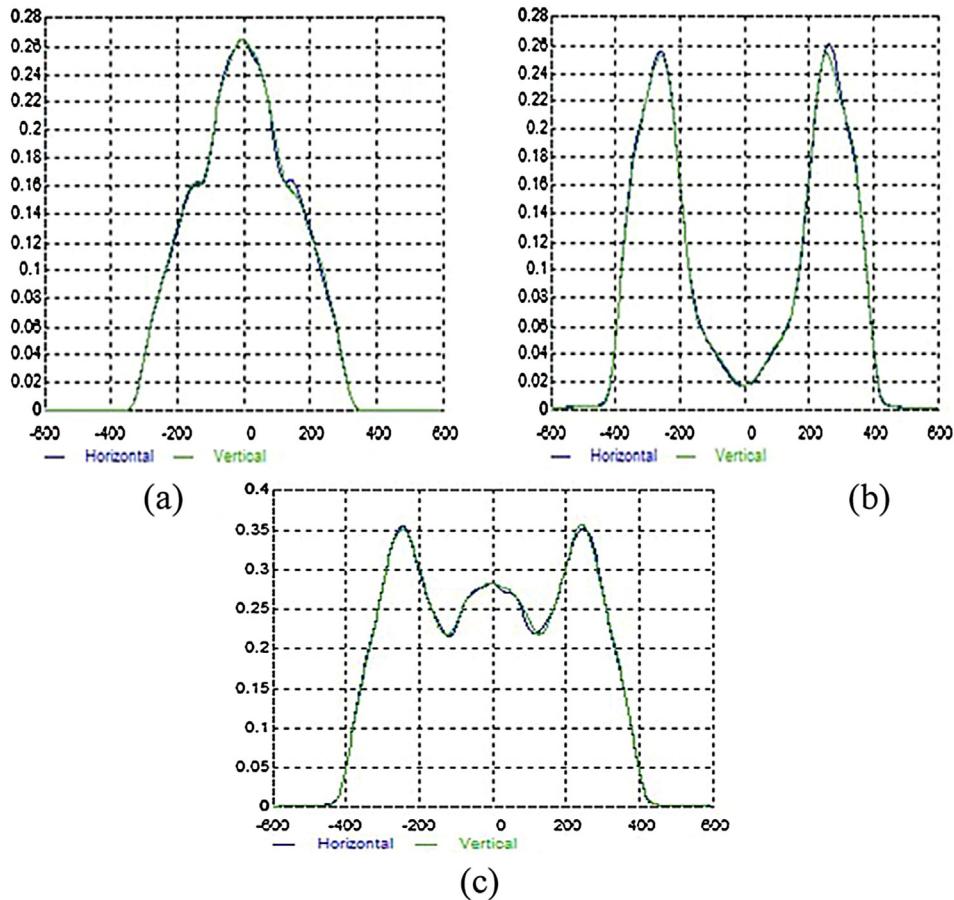
## 1. Introduction

With the widespread use of LED in the lighting area, the lens design of the LED uniform illumination is becoming the hot research topic. It is well known that the freeform surface lenses possess unique ability with freely allocation light intensity to achieve uniform illumination of LED. However, the traditional design method which regards the extended light source as a point source is not applicable to a small size of lens [1–5]. Therefore various kinds of optimization methods of freeform surface lenses for uniform illumination of LED were developed. Y. Luo et al. proposed a feedback optimization method based on the establishment and modification of the feedback function [6]. X.X. Luo et al. proposed a method which the optimization function and the feedback function were established in ZEMAX environment [7,8]. E. Chen et al. proposed an optimization method which the MATLAB software and the optical software were alternatively used [9]. The common characteristics of the mentioned methods are as follows. The initial structure of the freeform surface needs to be calculated, and the feedback function and optimization function need to be established beforehand.

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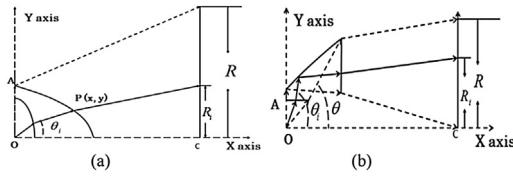


**Fig. 1.** Three-dimensional model diagram. (a) Refractive structure. (b) Reflective structure 1. (c) Reflective structure 2.

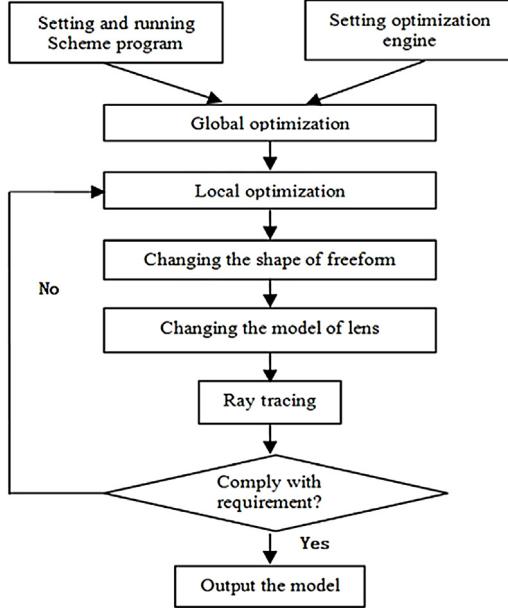


**Fig. 2.** Separation of curve illumination for refraction lens. (a) The illumination distribution produced by other part. (b) The illumination distribution produced by central part. (c) The superposition of both parts.

In this paper, an optimization method of freeform surface lens for uniform illumination of LED based on non-imaging optics is proposed. Regular quadratic curve is used as the initial model, and the quadratic B-spline, Scheme language and optimization engine are used in combination to achieve the local control and optimization of the freeform surface. Several types of the systems are designed with the proposed method.



**Fig. 3.** The analysis model of local optimization. (a) The refraction model. (b) The reflection model.



**Fig. 4.** Flow chart of the optimization design.

## 2. The design of lens and curve fitting

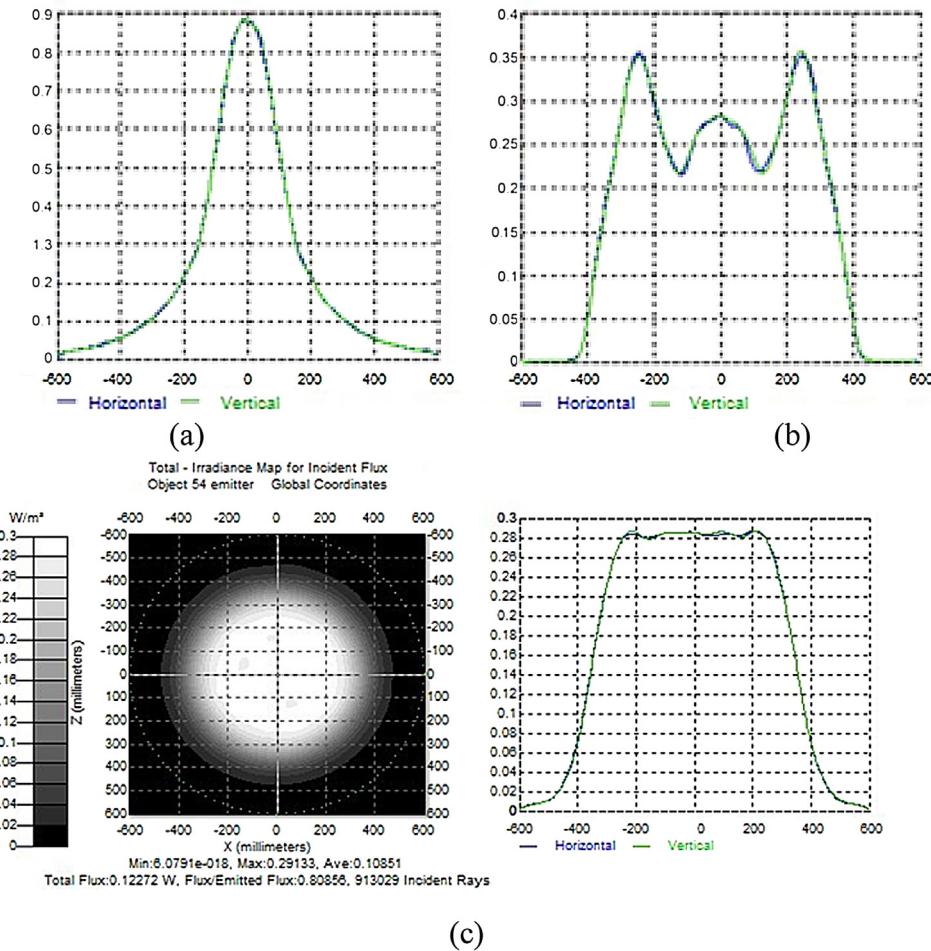
The structures of the lenses are assumed to be rotationally symmetric and shown in Fig. 1. X axis is taken as the rotationally symmetric axis. Fig. 1(a) is the refractive structure, and surface ③ is the freeform surface. Fig. 1(b) is the reflective structure, and surface ② is the freeform surface. Fig. 1(c) is the total internal reflection structure, and surface ① and surface ② are the freeform surfaces. Other surfaces are the known regular surfaces. The regular quadratic surface is used as the initial freeform surface, and the quadratic B-spline is chosen for fitting the freeform curve and extracting the control points of freeform curve.

## 3. Optimization

### 3.1. The global optimization and the local optimization of freeform surface

Usually, the optimization of the freeform surface lens is a global optimization, which all control points are optimized. It is shown that the illumination distribution at the central location of the target is always weaker than the other location. The refractive model is chosen as an example. For demonstration the lens is divided into two parts including the central part and the other part. The illumination distribution at the target produced by the central part of the lens is shown in Fig. 2(a), and the illumination distribution at the target produced by the other part is shown in Fig. 2(b). The illumination distribution produced by both parts is shown in Fig. 2(c), which is a superposition of Fig. 2(a) and (b). It can be seen that the illumination value at the central location in Fig. 2(a) is comparable with the peak value in Fig. 2(b), but in Fig. 2(c), the illumination value at the center is only 77% of the peak value.

The central part of the freeform surface lens is much easier to control due to the smaller ray deflection angle. Therefore a local optimization method is proposed which is for the central part only. In this way, less rays are gathered in the radius of 0.2 m–0.4 m in Fig. 2(a), and more rays are gathered near the radius of 0.16 m. However, the local optimization brings about unsmooth and disconnection of freeform surface owing to the huge difference between the initial and the final model. A method of combination of global optimization and local optimization is put forward. On the other hand the quadratic



**Fig. 5.** The illumination curves of the refractive lens. (a) Before optimization. (b) After global optimization. (c) After local optimization.

**Table 1**

Optimization time in different deflection angle.

Deflection angle	0–30°	30°–60°	60°–90°
Optimization time	About 6 min	About 7 min	About 10 min

B-spline is more convenient for the local modification compared to other fitting methods. Therefore it is used to conduct the global and local optimization. It takes about 30 min to accomplish a round of global optimization, whereas it is less than 10 min for a round of local optimization. The smaller the deflection angle is, the less the optimization time as shown in Table 1.

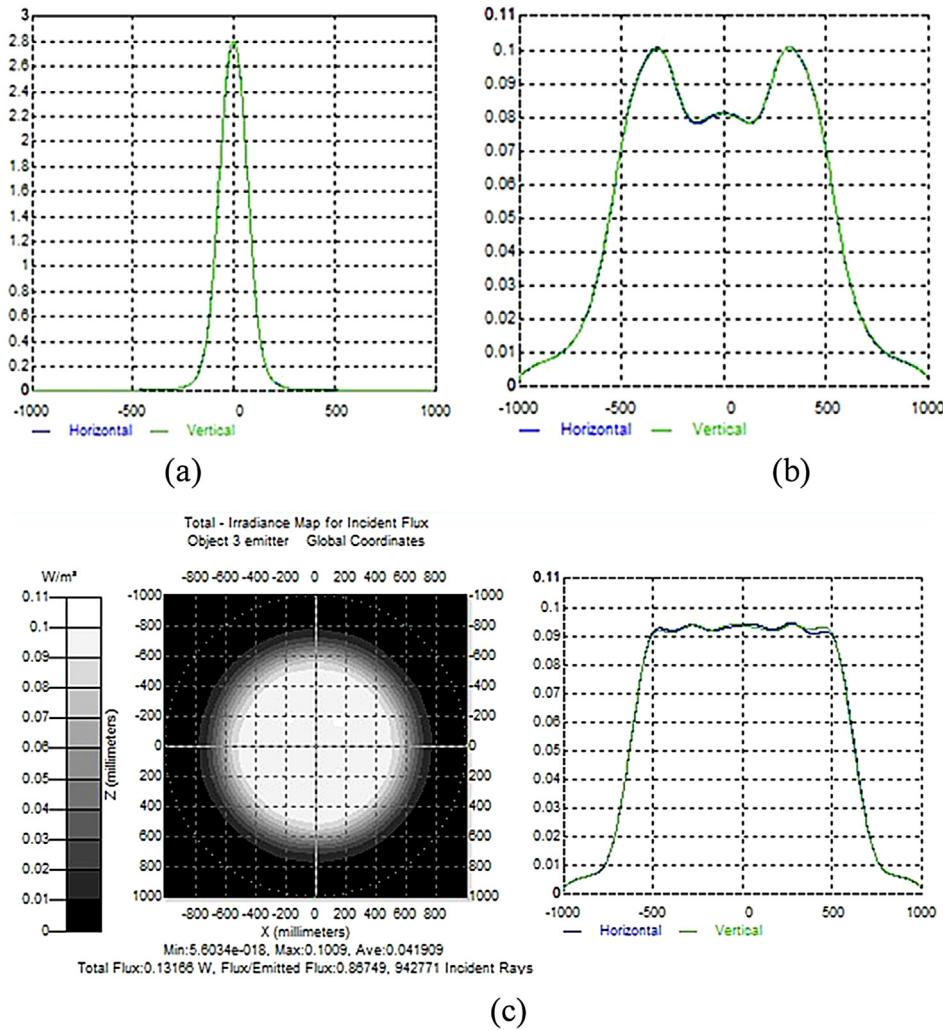
### 3.2. Optimization design process of freeform lens

Fig. 3 is the analysis model of local optimization, where (a) is for refraction surface and (b) is for total refraction surface. As shown in Fig. 3(a),  $\theta_i$  is the angle formed by the  $i$ th refraction ray from the first refractive surface and the X axis ( $\theta$  is the maximum refraction angle),  $P$  is the intersection point of the ray and the second refractive surface,  $R_i$  is the corresponding radius at the target surface, and  $R$  is the radius of the entire spot. The exit angle  $\theta$  and the target surface  $R$  are averagely divided into  $n$  parts. Then we have

$$\theta_i = \frac{\theta}{n} i, \quad R_i = \frac{R}{n} i \quad (1)$$

Deduced from Eq. (1), we have the correspondent relationship between  $\theta_i$  and  $R_i$ :

$$\theta_i = \frac{\theta}{R} R_i \quad (2)$$



**Fig. 6.** The illumination curves of the reflective lens 1. (a) Before optimization. (b) After global optimization. (c) After local optimization.

If the illumination value near the radius of  $R_i$  is lower, the local freeform curve near to the angle of  $\theta_i$  needs to be optimized. The optimization should be controlled by three control points, and only the middle control point is set as the variable normally.

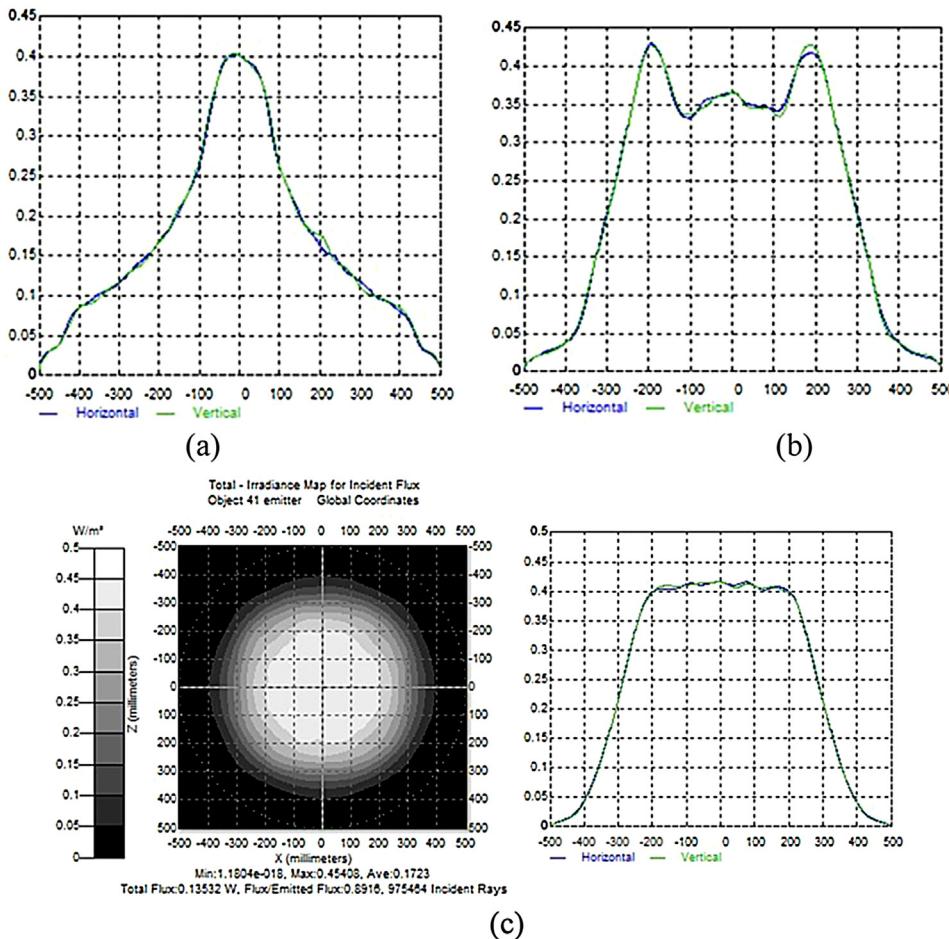
The total reflection model can be analyzed in the same way, and the correspondent relationship between  $\theta_i$  and  $R_i$  is as:

$$\theta_i = \frac{90^\circ - \theta}{R} R_i \quad (3)$$

[Fig. 4](#) is the flow chart of the optimization design. The first step is to set an optimization engine and write a Scheme program including LED chip, lens, target, as well as some of their properties. The next is to conduct a round of global optimization. All of control points are set as variables for the optimization, and the result is as the initial value of local optimization. The last is to conduct local optimization. This optimization is at some local parts of the freeform surface where the illumination uniformity is bad. Few of control points are set as variables and several rounds of the optimizations are needed until the result meets the requirements of the illumination requirement.

#### 4. The design example and simulation results

In this paper, several lenses of spotlights for different applications have been designed. The optical design parameters are shown in [Table 2](#). The 1 mm × 1 mm LED is used as the light source. The material of the lens is PMMA and the number of ray



**Fig. 7.** The illumination curves of the reflective lens 2. (a) Before optimization. (b) After global optimization. (c) After local optimization.

**Table 2**

Optical design parameters.

Parameter	Value
Light source	1 mm × 1 mm
LED chip	Lambert Radiation
Lens aperture	About 9 mm
Lens material	PMMA

tracing is 1,000,000. It is expected to achieve uniform illumination at the target 1 m away from the source. The uniformity is defined as

$$E_{\text{uniform}} = \frac{E_{\min}}{E_{\max}} \times 100\% \quad (4)$$

**Fig. 5** is the illumination curves with the refractive lens, which (a) is the illumination distribution before optimization, (b) is the illumination distribution after a round of global optimization, and (c) is the illumination distribution after further local optimization. It can be seen that there is no uniformity on the target within the field of view of ±14° before optimization. After a round of global optimization, the illumination uniformity reaches about 72%, and the illumination value is low within the radius of 0.1 m at the target. After further local optimization, the uniformity reaches over 97% within the field of view of ±14°, which is a great improvement.

The optimization process of other two kinds of lenses is the same as the refractive lens. **Fig. 6** is the illumination curves with the reflective lens 1, which (a) is the initial illumination distribution before optimization, (b) is the illumination distribution after a round of global optimization, and (c) is the illumination distribution after further local optimization. It can be seen that there is no uniformity on the target within the field of view of ±30° before optimization. After a round of global optimization, the illumination uniformity reaches about 78%, and the illumination is very low within the radius of 0.2 m at the target. After further local optimization, the uniformity reaches over 96% within the field of view of ±30°. **Fig. 7** is the

**Table 3**

Parameter of lens.

Lens	Diameter	Thickness	Field of view	Radius on the target	Uniformity	Energy efficiency
Refractive	8.8 mm	7 mm	±14°	600 mm	97%	80.9%
Reflective 1	8.5 mm	7 mm	±30°	1000 mm	96%	86.7%
Reflective 2	9.5 mm	4 mm	±12°	450 mm	95%	89.2%

illumination curves with the reflective lens 2, which (a) is the initial illumination distribution before optimization, (b) is the illumination distribution after a round of global optimization, and (c) is the illumination distribution after further local optimization. Again there is no uniformity on the target within the field of view of ±12° before optimization. After a round of global optimization, the illumination uniformity reaches about 77%, and the illumination is quite low within the radius of 0.1 m at the target. After further local optimization, the uniformity reaches over 95% within the field of view of ±12°.

The specific parameters of the three models are shown in Table 3. The diameter and thickness of the lenses are less than 10 mm. The uniformity is respectively 97%, 96% and 95% within the field of view of ±14°, ±30° and ±12°. The energy efficiency is respectively 80.9%, 86.7% and 89.2% for the three models. These are compared with reference [7] where the uniformity is 92% within a field of view of ±12° and the energy efficiency is 83.6%.

## 5. Conclusions

Based on non-imaging optics theory, a new optimization method of freeform surface lens for LED uniform illumination is presented. The quadratic B-spline, the Scheme language and the optimization engine are applied to achieve the local control and optimization of freeform surface lens. It is shown that the maximum uniformity of 97% and the maximum energy efficiency of 89.2% are achieved at the target surface 1 m away from the light source. As compared with traditional optimization methods in the design of LED uniform lens, the proposed method possesses advantages such as less reliability on initial model, short optimization time, higher illumination uniformity, and good versatility as well.

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