# Research of TIR LED Collimation System Based on Freeform

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**Abstract:** In order to collect a wide angle range light to receive the collimating beam of a small divergence angle, a highly efficient, compact, TIR collimating system has been designed and optimized. The collimating system adopts a hybrid structure with TIR style. First, calculate the initial structure of the collimating system according to Snell's law and equal focal length principle. Then optimize the initial structure using Lighttools optical design software. Finally, the best LED collimating system has been successfully designed. According to the results of the design, the semi-diameter of the TIR collimating system is 20mm, the diameter is 25mm. The collimating angle is 1.5° . With the light absorption loss of the material and reflection loss of the interface have already been fully considered，the light energy utilization rate is as high as 89.5%. The initial structure of TIR-type LED collimator is designed by Snell's law and equal focal length principle, and then it is optimized by the Lighttools optical design software, so that light energy utilization ratio and uniformity of illumination in the target surface are improved. In addition, TIR-type collimating system, which is small and easy to use, not only has a high light energy utilization ratio but also a compact structure.

**Key words:** non-imaging optics; freeform surface; Collimators; TIR; LED

## 1 Introduction

Because LED's (Light Emitting Diode,）energy saving effect is remarkable, small volume, light weight, low driving voltage, low power consumption, long life, and excellent color etc, its application fields are expanding more and more widely, especially in automotive lighting, smoke alarm, security, stage lighting, television lighting, advertising lighting, street lamps, and other fields. LED source in lighting applications, researchers focus on the question of how to improve the light energy utilization and energy distribution in accordance with the special requirements to meet the specific situations of light distribution requirements in the lighting application of LED.

LED's light-emitting mechanism determines its luminescence properties, while LED light source has small volume, light weight, long service life and the advantages of energy conservation and environmental protection, but it is difficult to collect and utilize owing to its larger divergence angle. The optical design of LED light source mainly achieved through reflective cup and normal lens. With the progress of science and technology, freeform surface is used more and more in the secondary light distribution design of LED in recent years. Freeform surface lens basically has the following several design methods:

1．The trial method[1], by revising the LED light distribution device parameters and using optical analysis software simulation verify the corresponding results, obtain the ideal freeform surface structure. This approach is time consuming, ineffective and seriously attached to the designer's experience.

2． Numerical solution[2-5] , according to Snell's law, the law of conservation of energy and the principle of

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equal optical path, by solving the differential equation of freeform surface data, the process of solving is heavily dependent on the initial boundary conditions, and it's difficult to calculate.

3．SMS (Simultaneous Multiple Surface) design method[6-9]. SMS method can be divided into two kinds of circumstance, two dimensions(2D) and three dimensions(3D), 2D design method is suitable for the axisymmetric optical device, and 3D design method is suitable for non-axisymmetric optical system.

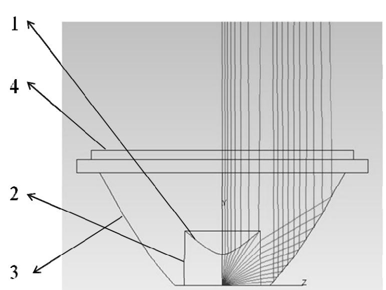
Using non imaging optics[10-11] to control the optical radiation transmission mainly can solve two kinds of problems: one is the collection of light, its focus is on the collection efficiency of light energy. Another is the distribution of light energy, it focuses on how to achieve a certain demand of light energy distribution. The TIR (Total Internal Reflection)[12, 13] type LED collimating system based on the free surface mainly used to solve the above two problems.

The freeform surface is often used in the application field of non-imaging, the freeform is irregular surface, therefore the theory of non-imaging optics is applied to design freeform surface[13-14]. 2D free-form surface design is essentially a series of discrete points obtained by ray tracing, then the discrete points are fitted in to a curve, then the curve rotates around the axis of symmetry to create a freeform surface. This is the effective method to design the rotational symmetry freeform surface. Fitting error is generated in the process of fitting discrete points into a curve, which lead to deviation of the illumination distribution in the target plate. In this paper, a freeform surface collimation system is designed by Matlab program to ray tracing, the collimation system uses a TIR compact structure, it is import into Lighttools software as the initial structure to further optimize the design, eventually improves the uniformity of illumination spot and light energy utilization.

## 2 Compact TIR LED collimating system

### 2.1 The structure of the TIR type LED collimating system

LED collimating system is the rotationally symmetric system, the diameter and thickness of the collimating system can be adjusted according to the requirements of the overall length of devices and the collimation angle. Common LED light source has been packaged, in order to improve the LED energy utilization, the secondary light distribution design can be used on the basis of the package. In this paper, the collimation system is designed with the secondary light distribution for LED. OSRAM SFH_4725S is selected as the LED light source. The receiving plate is located 100 meters from the light source, the material of the collimation system is PMMA (polymethyl methacrylate), PMMA has high light transmittance, small density and easy to be injection molding, etc. The collimating system profile is shown in Fig.1.




1、The first incident surface U；2、The first incident surface D；3、The total internal reflection surface；4、The exiting surface

Fig. 1 TIR LED collimator system

LED collimating system is mainly composed of three surface: the number 1 and 2 in figure 1 are the first incident surface, U surface receives the small angle light of LED; D surface receives the large angle light of LED. The number 3 is the total internal reflection surface. The number 4 is the finally refraction surface.

## 2.2 The design of the TIR type LED collimating system

The key technology of collimating system design is the design of the LED collimating lens. The design is based on non-imaging optics theory, which requires the incident light energy transmit to the receiver to the greatest extent. The design of LED collimating lens is based on two-dimensional calculation, the 2D curve rotates around its central axis and then get the rotational symmetrical freeform surface which constitutes the initial structure of collimation system.

The small angle rays emitting from the LED light source enter into the collimating system through the first incident surface U, and then exit by the refract surface, finally achieve the goal of collimation. The large angle rays emitting from LED source go into the collimating system through the first incident surface D, and then are total internal reflected through the total reflection surface, finally exit by the refract surface. The exit rays achieve the goal of collimation.

TIR LED source is located in the origin of coordinates, assuming that the LED source is the ideal point source. Efficiency of the first incident surface decide the energy utilization of the whole collimation system, thus the light distribution of the first incident surface must be reasonable.

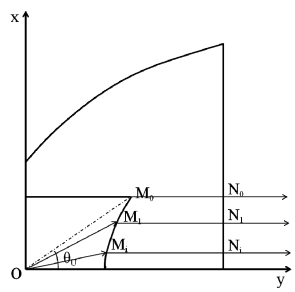



Fig. 2 The schematic diagram of the first refraction surface U.

## 1、The design of the first incident surface

Fig. 2 is the schematic diagram of the first incident surface, firstly set (r, 0) as the coordinates of M0. $OM_0$ is dividing line of the first incident curve U and the first incident curve D, The rays within $0 \sim \theta_U$ scope of LED source are collimated after refraction in the first incident curve U . $\theta_U$ are divided into N equal parts, LED source has N + 1 rays matching, and the direction of each light can be obtained. $OM_0$ is incident light vector, $M_0N_0$ is refracted light vector. The refraction point $M_0$ can be obtained according to Snell's law. The coordinates, normal vector and tangential direction of $M_0$ are known at this time. $M_0$ tangential line through $M_1$, the coordinates, normal vector and tangential direction of $M_1$ can be calculated according to Snell's law and equal optical path principle. And so on, the N+1 coordinates, normal vector and tangential direction of points ($M_0$, $M_1$,... $M_N$) can be calculated. A series of discrete data points calculated are fitted into a smooth freeform curve, and then we can get the equation of the first refracted curve U.

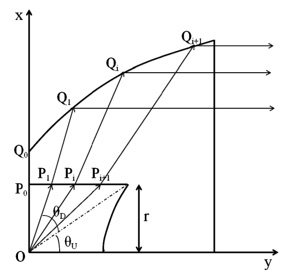


Fig. 3. The schematic diagram of the total internal reflection.

The wide angle rays within the scope of $\theta_U$~$\theta_D$ emitting form LED source enter the collimation system inside after refracted through the first refracted curve D, this part of the refracted surface is cylinder model. Considering the actual injection mold release, the cylinder should have draft angle of 2° .

The rays emitting form LED source are divided into two parts, the rays from 0 to $\theta_U$ go through two refraction inside the collimation system. When the $\theta_U$ Angle increases, the luminous flux in this part increases, the loss of energy will decrease, but this part rays will shift outward, which produce the non-collimation beam. When the $\theta_U$ angle is reduced, the luminous flux and the efficiency in this part will decrease reduced. So we must balance the relationship between the collimation angle and the efficiency. The initial selection of $\theta_U$ equal 45 °.

## 2、The design of total internal reflection surface

The total reflection surface is the main part of the distribution LED luminous flux. It mainly depends on the rationality of the total internal reflection surface if the collimation system designed can satisfy the design requirement. Fig.3 is formation process of the total internal reflection surface. $OP_1$ is the edge ray emitting form the LED source, when $OP_1$ is refracted at $P_1$ point of the interface of two medium, When the ray pass through the optical dense medium from optical thinner medium, it deviates from the original direction. The incident angle and the refractive index of materials are known, according to the law of refraction, we can obtain the refracted ray $P_1O_1$. When the incident angle of the refracted ray $P_1O_1$ is greater than the critical angle at point O1, total internal reflection phenomenon will occur. So we will control the curvature of $O_1$ point, make the ray $P_1O_1$ occurs total internal reflection at $O_1$ point. The total reflected ray emits from the system into collimating ray at last.

$$\sin I_C = \frac{1}{n} \tag{1}$$

Ic is the critical angle in the formula (1). Using the iterative algorithm described above, we can calculate coordinates, normal direction and tangential direction of a series of discrete points. The curve equation of the total internal reflection surface can be obtained by fitting the discrete data points obtained by the calculation.

## 3、The design of exit refraction surface

The forms of the collimation system exit surface include plane, cone surface and quadric surface etc. The rays have changed into a collimated beam after passing through the first refraction surface and the total internal reflection surface, so we choose a plate as the exit refraction surface. Fig. 4 is the initial structure of collimation system.

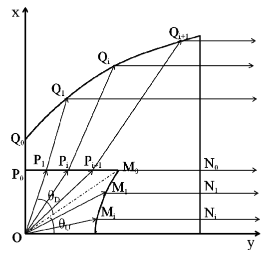


Fig. 4 The initial structure of collimating system.

## 3 The simulation analysis of the initial structure of collimation system

The initial structure model has been established by the optical design software Lighttools. OSRAM SFH_4725S is selected as LED source, and the LED source is set to 5 million rays. The initial structure of the system was simulated by Monte Carlo ray tracing. From the results of simulation analysis Fig. 5 and Fig.6, we can see that the energy utilization of the LED collimation system initial structure is 85.6%. The intensity of illumination is lower in the center of the target surface, the peak of intensity illumination appears in the $1.2^{o}$ ~ $2.3^{o}$ half-angle field of view. The divergence angle of collimation system is ± 3.4 °. The illumination distribution on the target surface is not uniform, and the energy utilization ratio of the LED collimation system initial structure is low.

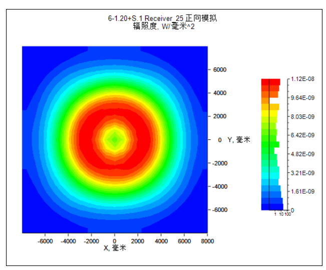


Fig.5 The irradiance map on the receiver surface of initial system.

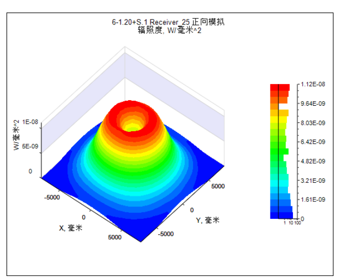


Fig.6 The irradiance 3D map on the receiver surface of initial system.

## 4 Optimization design of the initial structure of collimation system

The initial structure of the collimation system is designed for the ideal point source, but the diameter of the actual LED source is $\Phi$ = 2.76mm, rather than point source, it will introduce errors. In addition, it will generate error when the calculated precision discrete data points are fitted into a curve. So the actual simulation results and theoretical design results are different. Therefore, the initial structure of LED collimation system needs to be optimized to improve the energy utilization and illumination uniformity on the target surface.

The coefficients of the curve equation which is fitted by the discrete data points are setted as discrete variables, and we can optimize the initial structure by the collimation optimization function in Lighttools software. Fig.7 and Fig.8 are the final optimization results.

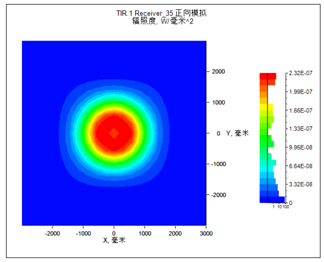


Fig. 7 The irradiance map on the receiver surface of optimized system.

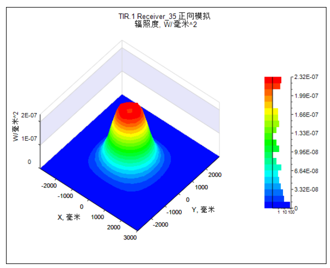


Fig.8 The irradiance 3D map on the receiver surface of optimized system.

According to contrast and analysis of the simulation results (Fig. 7, Fig. 8) of the optimized system and the simulation results of the initial system (Fig. 5 and Fig. 6), the utilization rate of energy is increased from 85.6% to 89.5%; the peak value of the intensity illumination appears in the center area of -0.5 ° to 0.5 °on the target surface (the target surface is 100 meters away from the LED source, the peak value of the intensity illumination appears in the circle with radius of 0.9m), the uniformity is 92.34% in this area, the uniformity formula is shown in formula (2).

$$U = \frac{U_{\max} - U_{\min}}{U_{\max} + U_{\min}} \times 100\% \qquad (2)$$

The optimized TIR collimation system focuses most of the energy emitted by the LED source in a circle of 2.6 meters radius at a distance of 100 meters from the LED source, the collimation angle meets the requirements of ± 1.5 °.

## 5 Conclusions

Based on the design idea of non-imaging optics, the TIR design method based on freeform surface is adopted. The calculated discrete data is fitted into a smooth curve, finally, three-dimensional free-form surfaces are generated by fitted curve revolving around the center axis of symmetry. So we can obtain the initial structure of the TIR type LED collimation system. The initial structure is optimized by Lighttools optical design software to improve the collimation and homogeneity of the collimation system. Finally we get the ideal collimation effect. The TIR LED collimation system can collect the rays in wide angle range of LED source, and produce a collimated beam with a divergence angle of ± 1.5$^{o}$. The energy utilization rate is up to 89.5%. TIR LED collimation system makes the optical path two fold, greatly reducing the system size, achieving the miniaturization of optical system. TIR LED collimation system improve the efficiency of collimation systems and uniformity, it has important theoretical and practical value.

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