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Miniaturized TIR Fresnel Lens for Miniature Optical LED Applications

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Light-emitting diodes (LEDs) have been investigated to expand their application to very thin electronic devices, including various optical components in a single device. In such applications, the collimation of light produced by LEDs using a conventional Fresnel lens can be bent at angles greater than 45°, whereas most LEDs radiate at solid angles greater than 60°. This paper describes a miniaturized total internal reflection (TIR) Fresnel lens for such miniature optical LED applications. The proposed lens reduces the solid angle of a LED from 60° to 12°, and was designed to have a thickness of less than 1 mm with eleven facets on a single side. The overall geometry of the TIR lens was calculated numerically using Matlab, and the central hyperboloid was designed using Code V.

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NOMENCLATURE

E = incident angle of an inner facet
n = refractive index of PMMA at 468 nm
P = angle of an external facet
r = radial distance from the lens center
T = angle between the interior faces and the external face
α = solid angle of the light source
ρ = radius of the TIR Fresnel lens

1. Introduction

Light-emitting diodes (LEDs) and laser diodes are used for illumination and in electronic devices. Multiple optical components are now encapsulated in single devices because of the rapid growth of personal mobile telecommunication devices, especially mobile phones and personal data assistants. LEDs have recently been the focus of attention aimed at expanding their application to these devices.

Efficient homogeneous illumination with vertical-cavity surface-emitting lasers or LEDs is increasingly used in the projection display industry, in which there are two areas of concentration: light sources and optical lenses. The ideal light source for this application produces light with a very small solid angle and good homogeneity; resonant-cavity LEDs are ideal for this.[1] Optical researchers and manufactures try to achieve extremely homogenous illumination patterns though well-developed optical design and manufacturing technologies.[2] Electro-optical light sources must overcome the limitations of their optical performance to be competitive with optical systems; the use of total internal reflection (TIR) Fresnel lenses is one way of accomplishing this. In addition to electro-optical applications, modified TIR Fresnel lenses have been used in high-efficiency photovoltaic modules for solar power generation,[3] rear projection displays,[4] and in applications for the automobile industry.

In all of these applications, the criteria for success of electro-optical systems are generally defined by the concentration efficiency. Concentration efficiency is the ratio of the usable flux received at a target to the total source flux emitted by a light source. The usable flux is typically defined with respect to a solid angle. The concentration efficiency of LEDs, however, is sufficiently low to restrict their application since the solid angle of LEDs is typically greater than 45°. Moreover, personal telecommunication devices are, at most, several millimeters thick. For this reason, LEDs require a special optical component, such as a miniaturized TIR lens, to meet this technical requirement.

The TIR lens was first applied to the control of the solid angle of non-imaging devices,[5] and was used in the beam forming of compact sources, such as incandescent filaments, LEDs, and arc lamps.[6] More recently, the TIR Fresnel lens has been used in LCD backlighting[7] and in the collimation of LEDs with diameters of several millimeters.[8]

Even though the TIR lens has been used with LEDs in various applications,[5-8] its functionality in terms of lens features has not been sufficient for use in miniaturized optical components. Aspheric lenses are generally used instead to achieve the required improvement in optical performance and miniaturization of the optical components.[9-12]

This paper proposes a TIR Fresnel lens for miniature optical LED applications such as collimating the light emitted from LEDs. To satisfy current technical requirements, the lens was designed to have a thickness of less than one millimeter and eleven facets on a single side to collimate the LED light effectively.

2. TIR Fresnel Lens Design

2.1 Design of single-sided TIR Fresnel facets

Fresnel lenses rely on refractive facets to duplicate the optical action of a conventional lens. Collimation of a point light source using a Fresnel lens cannot extend the maximum bend greater than 45°, whereas most LEDs radiate into solid angles greater than 180°. Adding prismatic facets (TIR faces) to a Fresnel lens can increase the bend angle capability to about 90°. TIR facets have three faces: an exterior face, an interior face, and the TIR face.

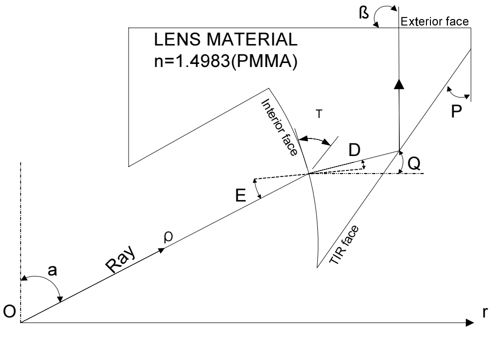


Fig. 1 Facet of a TIR Fresnel lens

For analytical convenience, we define P to be the angle between the TIR faces and the system axis. The light rays with solid angle α make angles E and D with the other two facets, as shown in Fig. 1. When a ray with incident angle E propagates to the inner facet, it refracts with refraction angle D, is reflected at the TIR face, and propagates to the air with bend angle β. Two constraints on these angles were regarded as design criteria: (1) the angle P will come too close to its maximum value unless the center of the lens is almost zero, and simultaneously, (2) P and E should be as large as possible for manufacturability at the cost of reflective losses. Assuming that the solid angle is constant, we can increase P by changing the sign of the incident angle E, as shown in Fig. 2.

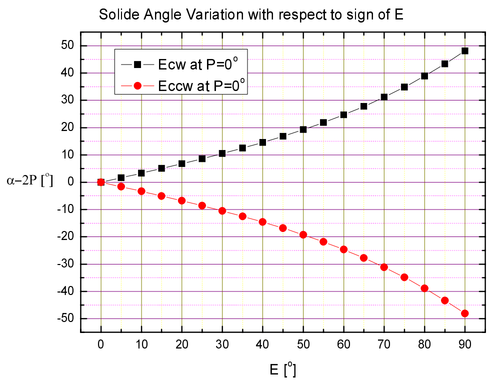


Fig. 2 Solid angle variation with respect to the sign of E

A TIR lens consists of a central aspheric lens and TIR facets. Figure 3 shows the design procedure for a TIR Fresnel lens. The geometry of each facet was developed in Matlab by calculating and choosing proper combinations of values of P, E, and α. The best P was the angle that could effectively reflect light from a large range of E to the external face. Consequently, the curvature radius of the facet was determined by adjusting α and E according to Eqs. (1)-(3),

$$\alpha = 2P + \sin^{-1}(1/n \cdot \sin E) - E, \text{ where } P \leq \sin^{-1}(1/n) \tag{1}$$

$$Q = 90° - E + D - \alpha \tag{2}$$

$$\rho = r \cdot \sin(\alpha + E) / \tan\alpha / (\sin\alpha \cdot \cos(\alpha + E) + \sin E) \tag{3}$$

The central aspheric lens was designed using Code V software.

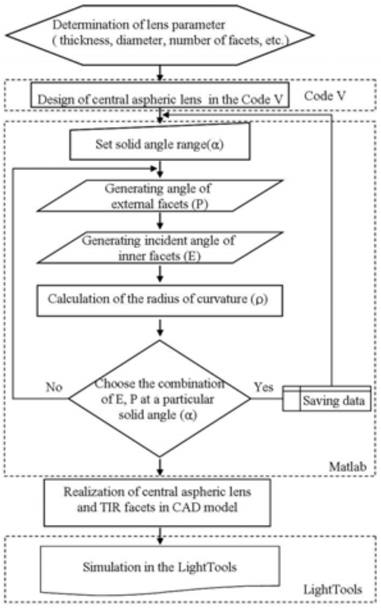


Fig. 3 TIR lens design procedure

After designing and generating the geometry of the TIR Fresnel lens, we converted it into a three-dimensional (3D) solid object in a computer-aided design (CAD) program for subsequent loading into the LightTools software. LightTools used Monte Carlo ray tracing to confirm the efficiency of the designed TIR Fresnel lens with the LED chip being modeled. The illumination analysis in LightTools traced million of rays coming from the LED (1.2 × 0.8 × 0.4 mm, $\lambda = 463 \pm 20$ nm). The lens was made of poly(methyl methacrylate) (PMMA), which is suitable for mass production processes like injection molding. Only the Fresnel loss was considered in the optical loss.

The design of the central part of the geometry was optimized using LightTools based on the target LED, as shown in Fig. 4.

The 3D model of the TIR lens used in LightTools is shown in Fig. 4. The interior faces were equally spaced and had aspheric geometries, while all values of P in a facet were constant for manufacturing simplicity. The central aspheric geometry, designed to have no vignetting losses, collimated light rays with a solid angle of less than 20°. The other part of the lens reduced the solid angle up to 12° full-width at half-maximum. In this part of lens, there was inherent light leakage of about 10° at each facet due to the manufacturing tolerances of the target lens. Figure 5 clearly illustrates the functionality of the lens, which reduced the solid angle of the LED from 60° to 12°. The designed lens was 0.5 mm thick and 3.0 mm in diameter.

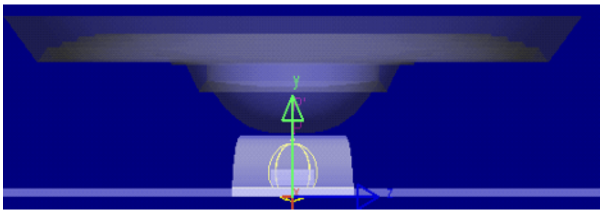
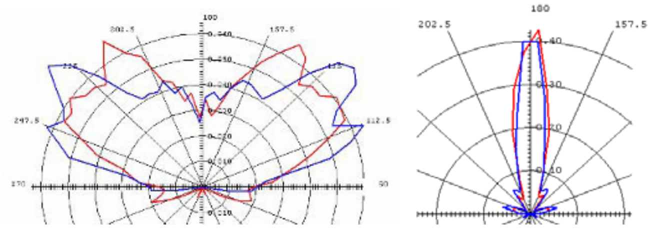


Fig. 4 3D visualization of the TIR lens with the modeled LED



(a) (b)

Fig. 5 (a) Far field illumination without TIR lens (b) Far field illumination with TIR len

3. Light Loss and Manufacturing Constraints

There are two main inherent losses of light rays in a TIR lens: light that reflects on the interior face and light that leaks between each facet. All of the light does not strike the interior face. Eliminating this leakage requires shading by the next facet inward, accompanied by a sharp rise to the maximum lens thickness; this makes manufacturing impossible. Therefore, the reduction of leaked light between the facets must be considered in the manufacturing constraints. All the light striking the interior face does not strike the TIR facet because the incident angle of the designed TIR Fresnel lens sometimes approaches 85°, which directly increases the reflectivity of the interior faces to about 25%. Of the light striking the TIR facet, 9% is also reflected.[5]

The design of the TIR Fresnel lens determines the collimation and intercept efficiency. After designing and generating the geometry of a proper TIR Fresnel lens, we must convert this geometry into a solid CAD model so it can be loaded into a conventional simulation program, such as LightTools or ASAP. These simulators will calculate the efficiency of the designed TIR Fresnel lens more accurately.

4. Illumination analysis

An illuminated view through the TIR lens showed a ghosting effect for the chip of the target LED in the near field. We determined, using LightTools, that there was less ghosting in the far field as the position of the artificial receiver was farther away from the LED chip. However, this would be even more complicated in real-world applications because of the scattered light on the surface of the LED and the TIR lens.

Since the inner facets only function as a surface to reduce the incident angle at the TIR face, the illuminated view contained regularly shaded patterns of the inner facets, which may appear as Moiré effects. We believe, however, there will be much less Moiré effect in real-world applications because of the relatively large solid angle. In LightTools, this pattern thus faded away as the position of the artificial receiver moved away from the LED. Unfortunately, if we are able to develop a more functional TIR Fresnel lens with a very small solid angle, the Moiré effect will be amplified when multiple lenses are used in an array.

5. Conclusions

We proposed a TIR Fresnel lens for miniature optical LED applications. Reducing the total thickness of the TIR lens to less than one millimeter was the most critical design criteria. The overall geometry of the TIR lens was calculated numerically in Matlab and the central hyperboloid was designed in Code V. The resulting TIR Fresnel lens design reduced the solid angle of LEDs from 60° to 12°.

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