LED Lens for Rectangular Beam with Small Divergence Angles

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(Received November 4, 2016 : revised November 18, 2016 : accepted November 21, 2016)

We have designed a new TIR(Total Internal Reflection) structure for generating an LED lens which can produce a rectangular beam with small divergence angle in two perpendicular directions for an optical guidance system. The lens can control the divergence angle in the horizontal direction to be a small value of about 8° with a 1 mm × 1 mm LED source, also in the vertical direction it can be about 7°, with optical collection efficiency higher than 0.83. After the lens is manufactured, the work demonstrates that the lens is suitable for an optical guidance system.

Keywords: Optical design, Lens design, LED
OCIS codes: (080.2740) Geometric optical design; (080.4295) Nonimaging optical systems; (230.3670) Light-emitting diodes

I. INTRODUCTION

In optical guidance systems, a rectangular beam is required, in addition the lighting divergence angles in two vertical directions must both be small. Different kinds of methods are proposed to achieve a rectangular beam for an LED [1-8]. Ref. [7] describes the rectangular beam in the form of divergence angles in two perpendicular directions. Because of the refraction limit, the divergence angle of the rectangular beam is hard to make smaller than the critical angle for the PMMA lens [7, 8]. Researchers have achieved lenses for rectangular beams and one of the divergence angles is smaller than 40° [7, 8], but the other divergence angle is larger than 120° in Ref. [7] and is 140° in Ref. [8], and the lighting divergence angle in other methods is large in two perpendicular directions [1-6].

Although the lighting divergence angle in Ref. [7, 8] is large in one direction, the method inspires us to achieve rectangular illumination with small divergence angle in two perpendicular directions. In fact, light in one direction is collimated by TIR structure in Ref. [7, 8], but divergence angle at the other direction can’t be controlled to be small enough. That is because the outer surface in Ref. [7, 8] has a refraction limit; the divergence angle can’t be smaller than 120°. As we know, a common TIR lens can obtain circular illumination with small divergence angle for an LED source [11-16]. And Chen in Ref. [9] proposed a new TIR collimating structure, the most important feature is that the TIR contour line can form an outer surface for the lens. If we improve this TIR structure to build the outer surface, it is possible to achieve a rectangular beam with small divergence angle in two perpendicular directions.

In this paper, we design a new TIR structure and apply it for achieving small divergence angle and easy processing, then build an outer surface for the lens, thus we can quickly generate a new LED lens for a rectangular beam with small divergence angle in two perpendicular directions.

II. A NEW TIR STRUCTURE DESIGN

The TIR structure in Ref. [9] is just for collimating lights and a circular beam, as shown in Fig. 1. The great advantage of the TIR structure is that the refractive line is on the outside. But from an industrial view, the acute angle at the middle position extended inward can’t be manufactured. Improved from this TIR, we designed a new TIR structure which can achieve different small divergence angles and is
FIG. 1. TIR structure in Ref. [9].

FIG. 2. A newly designed TIR structure.

The TIR structure consists of four surfaces: surface $a$, surface $b$, surface $c$ and surface $d$. The light source is located in the origin of the coordinate axis. $\beta$ is the angle between the incident ray and the $z$-axis. $\gamma$ is the angle between the emergent ray and the $z$-axis. The refractive indexes of two mediums are $n_1$ and $n_2$.

The TIR structure generates a mapping between $\beta$ and $\gamma$

\[
\begin{align*}
(\beta_1, \beta_2, \cdots, \beta_k) &\rightarrow (\gamma_1, \gamma_2, \cdots, \gamma_k) \\
(\beta_1, \beta_2, \cdots, \beta_N) &\rightarrow (\gamma_{N+1}, \gamma_{N+2}, \cdots, \gamma_{N+1}) \quad \gamma_N \geq 0
\end{align*}
\]

Where $\beta_k$ and $\gamma_k$ are the boundary angles between surface $a$ and surface $b$. When $0 < \beta < \beta_k$, incident rays spread to surface $a$. For any point $B_i$ on that surface, the angles of incident ray and emergent ray corresponding to point $B_i$ are $\beta_i$ and $\gamma_i$. According to Snell’s Law, if coordinates of point $B_{k+1}$ are known, then we can obtain coordinates of point $B_{k+1}$ by

\[
\begin{align*}
\text{In}_i &= (\sin(\beta_i), \cos(\beta_i)) \\
\text{Out}_i &= (\sin(\gamma_i), \cos(\gamma_i)) \\
\left[1 + \left(\frac{n_2}{n_1} \gamma_i - 2 \frac{n_2}{n_1} (\text{Out}_i \cdot \text{In}_i)\right)^2\right]^{1/2} \cdot \text{N}_i &= \text{Out}_i - \frac{n_1}{n_2} \cdot \text{In}_i, i \leq k - 1 \\
\left(\text{B}_{k+1} - \text{B}_i\right) \cdot \text{N}_i &= 0
\end{align*}
\]

Where $\text{N}_i$ is the normal vector at point $B_i$. Point $B_{k+1}$ is located on the extension of line $\text{OB}_k$. If coordinates of $\text{B}_1$ and $\left[\text{B}_1 \text{B}_{k+1}\right]$ are known, coordinates of all points $B_i$ can be obtained.

When $\beta_k < \beta < \pi / 2$, incident rays spread to surface $d$ first. The emergent ray at the direction of $\text{M}_i \text{B}_k$ has the angle $\gamma_{k+1}$. The coordinates of point $M_1$ can be calculated by

\[
\frac{\text{M}_i \text{B}_{k+1}}{\left|\text{M}_i \text{B}_{k+1}\right|} = (\sin(\gamma_{k+1}), \cos(\gamma_{k+1}))
\]

Total reflection happens at surface $d$, the angles of incident ray and emergent ray corresponding to point $M_i$ are $\beta_{N-1-i}$ and $\gamma_{k+i}$, then tangent vector on point $M_i$ can be expressed as

\[
\text{R}_i = (\sin(\beta_{N-1-i}) + \sin(\gamma_{k+i}), \cos(\beta_{N-1-i}) + \cos(\gamma_{k+i}))
\]

If coordinates of point $M_i$ are known, then we can obtain coordinates of point $M_{i+1}$ by

\[
\begin{align*}
\frac{\text{OM}_{i+1}}{\left|\text{OM}_{i+1}\right|} &= (\sin(\beta_{N-i}), \cos(\beta_{N-i})) \\
\frac{\text{R}_i}{\left|\text{R}_i\right|} &= \frac{\text{OM}_{i+1} - \text{OM}_{i}}{\left|\text{OM}_{i+1} - \text{OM}_{i}\right|}
\end{align*}
\]

After total reflection, rays are reflected by surface $d$ to surface $c$. We let the rays go through surface $c$ vertically. So the angle of emergent ray corresponding to point $L_i$ is also $\gamma_{k+i}$. If coordinates of point $L_{k+1}$ are known, then we can obtain coordinates of point $L_i$ by

\[
\begin{align*}
\frac{\text{M}_i \text{L}_{i+1}}{\left|\text{M}_i \text{L}_{i+1}\right|} &= (\sin(\gamma_{k+i}), \cos(\gamma_{k+i})) \\
\left(\text{M}_i \text{L}_{i+1} - \text{M}_i \text{L}_i\right) &= 0
\end{align*}
\]

According to Eq.(1)-(6), we can get the TIR structure.
III. LENS GENERATION

Based on the designed TIR structures, the lens can be constructed as follows:

1. Constructing inner surface. According to Ref. [7], a rectangular beam with small divergence angle at one direction can be obtained by the TIR structure [10] as shown in Fig. 3. The key is in rotating the TIR structure around the x-axis 180° to form the inner surface, then a cylindrical wave front with the x-axis is formed, all of the LED source lights can be collimated by it. With the TIR structure rotated around the x-axis, a cylinder inner surface can be formed, as shown in Fig. 4.

2. Constructing outer surface with designed new TIR structure in Fig. 2. Based on the inner surface a cylindrical wave front around the x-axis is formed, we construct the outer surface by lofting the improved TIR structure along x-axis, as shown in Fig. 5. Thus the divergence angle at the y-axis direction can be controlled to be different small angles. With the TIR structure in Fig. 2 lofting along the x-axis at the length in line with the width of the inner surface, an outer surface can be formed, as shown in Fig. 5.

3. Generating lens by closing other planes. With two surfaces combined, planes at the bottom and two sides must be closed, thus we can obtain all of the lens surfaces and build the lens model, as shown in Fig. 6.

IV. RESULTS

In order to demonstrate our new method, half-divergence angle $\gamma_{N+1}$ of new designed TIR structure is set as 3.5°. Refractive index of material PMMA is 1.4935 without loss. Since an LED source produces a rotationally symmetric Lambertian light distribution, in order to ensure uniformity as much as possible, we take sample $\beta_i$ and $\gamma_i$ based on equivalent-flux division [6], the detail mapping form between $\beta_i$ and $\gamma_i$ is

\[
\begin{align*}
\int_0^{\frac{\pi}{2}} \frac{\cos \beta d\beta}{N-1} & = \frac{i-1}{N-1}, 0 \leq \beta_i \leq \pi / 2, 1 \leq i \leq N \\
\int_0^{\frac{\pi}{2}} \cos \beta d\beta & = \frac{i-1}{N-1}, 0 \leq \beta_i \leq \pi / 2, 1 \leq i \leq N \\
\gamma_{i} & = \frac{i-1}{N-1} \gamma_{i+1}, 1 \leq i \leq k \\
\gamma_{i} & = \frac{i-2}{N-1} \gamma_{i+1} + \gamma_{i} = N+1
\end{align*}
\]
After ray tracing for the lens, we get the illumination distribution at a distance of 4m and angular distribution, as shown in Fig. 7. From the distribution we can know the divergence angle in the horizontal direction is almost 8° and the divergence angle in the y-axis direction is almost 7°, and the light collection efficiency is about 0.839. But it is not a complete rectangular distribution, and symmetric dark zones exist in the angular distribution in Fig. 7(b). The reason is that the special shape of the improved TIR structure in Fig. 2, emergent lights between $\gamma_{k+1}$ and $\gamma_{k+2}$ will have the broadest range in a distance of 4m among other equivalent-flux lights, and the slant surface formed by $B_k B_{k+1}$ aggravates it.

V. DISCUSSION

In order to ensure complete rectangular distribution as much as possible, we adjust the improved TIR structure for a new outer surface, as shown in Fig. 8. After reflecting lights have the half divergence angle range from $\gamma_1$ to $\gamma_N$, thus lights will overlap in the far-field to ensure complete rectangular distribution.

Also we take sample $\beta_i$ and $\gamma_i$ based on equivalent-flux division, the detail mapping form between $\beta_i$ and $\gamma_i$ is

$$
\begin{align*}
\frac{\int_{\beta_0}^{\beta_i} \cos \beta d\beta}{\int_{\beta_0}^{\beta_N} \cos \beta d\beta} &= \frac{i-1}{N-1}, 0 \leq \beta_i < \pi, \frac{i}{2} \leq i \leq N \\
\gamma_i &= \frac{i-1}{k-1} \gamma_{N+1}, 1 \leq i \leq k \\
\gamma_i &= \frac{i-k}{N-k} \gamma_{N+1}, k+1 \leq i \leq N+1
\end{align*}
$$

With the new lens we also use a 1mm×1mm LED source with 0.5 million rays for the simulation. After ray tracing for the lens, we get the illumination distribution at a distance of 4 m and angular distribution, as shown in Fig. 9. From the distribution we know that the divergence angle in the horizontal direction is almost 8° and divergence angle in the y-axis direction is almost 7°, in addition, the light collection efficiency is about 0.840. At the same time, we also get illumination distribution at a distance of 1m and 200 m, as shown in Fig. 10. We can see that at a long enough distance it is almost a complete rectangular distribution without divergence angles changing.

Based on the adjusted simulation result, we fabricate it by precision machine tool processing. The size of the lens is 102 mm × 38 mm × 53 mm, as shown in Fig. 11.

Figure 12 shows the experimental result of the fabricated lens at a distance of 4m with a red CREE XP-E. The divergence angle in the vertical direction is about 7° which coincides with simulation result, also the divergence...
angle in the horizontal direction is 8° at the center strong-illumination zone, in addition, illumination at the center has better uniformity than the simulation result. However there are weak-illumination zones out of the center at horizontal directions, the optical efficiency is about 0.75 which is lower than simulation result. That is because the inner surface is closer to the LED source, and unavoidable machining error of the inner surface will bring extension of the divergence angle in the horizontal direction. After all, divergence angles are both small through overcoming the refractive limit in two directions. A rectangular beam is obtained, divergence angles in two perpendicular directions are sufficiently small.
VI. CONCLUSION

We designed an LED lens for an optical guidance system to achieve a rectangular beam with small divergence angle in two perpendicular directions. Through a well-known collimator we can build an inner surface. Also we designed a TIR structure for achieving small divergence angle and easy-manufacturing, and constructed an outer surface, thus we can generate an LED lens. Simulation results show that the lens can control the divergence angle in the horizontal direction to be as small as about 8° with a 1 mm × 1 mm LED source, and in the vertical direction it can be about 7°, meanwhile a rectangular beam can be obtained with the optical collection efficiency higher than 0.83. After the lens has been fabricated, the experimental results almost coincide with simulation results, in addition demonstrating illumination at the center with better uniformity than the simulation result. However, there are weak-illumination zones out of the center in horizontal directions. That is because the inner surface is closer to the LED source, and unavoidable machining error of the inner surface will bring extension of the divergence angle in the horizontal direction. Finally, a rectangular beam is obtained, divergence angles in two perpendicular directions are small enough. The designed lens can be applied to an optical guidance system. In further study, it is significant to form a clear boundary by eliminating weak-illumination zones out of the center.

ACKNOWLEDGMENT

This work was supported by the Navy Scientific Research Foundation of China (No. 417210973).

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