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Laser beam shaping with an ellipsoidal lens

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ABSTRACT

This paper presents a semiconductor laser beam shaping system that can collimate the irradiance profile effectively by using an ellipsoidal lens. Geometrical optics analysis based on the ray tracing method is done and the formulas to calculate the shape of ellipsoidal lens are given. Both the theoretical and experimental result show that the laser beam system works effectively; the divergence angle is reduced to less than 1° in the fast-axial direction. By using epoxy resin, this shaper collimates a semiconductor laser beam and packages the laser diode (LD) at the same time, which simplifies the manufacturing process and greatly reduces the LD volume. Because of the small volume, low-cost, high rigidity and easy fabrication, the shaper is of great value in the field of semiconductor laser diode applications.

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1. Introduction

Because of their low price and small size, semiconductor lasers have been widely used in many fields. However, the semiconductor laser diodes' (LDs') potential applications are limited by their poor beam quality, which is ascribed to the large divergence angle and to the Gaussian irradiance profiles. In order to make the light travel far enough and to retain the light intensity in a small area, many fields, including military and commerce, need the rays emitted from LDs to be parallel. To achieve as small as possible divergence angle beams, experts all over the world have done a great deal of research in beam shaping, and some excellent work and designs have been carried out [1–4]. For single-mode lasers, two of familiar kinds of shaping systems are shown as follows.

The first method uses a plano-aspheric lens pair to shape the beams with Gaussian irradiance profiles, as shown in Fig. 1.

The first aspheric surface redistributes the rays in such a way as to transform the profile, and the second aspheric surface recollimates the beam [5,6]. This refractive beam shaper can be used to collimate the irradiance profile and get a flat-top beam at the same time, which is substantially superior to a Gaussian beam for illumination applications.

Another design uses a hyperboloid cylinder-plane lens for shaping the laser beam [7], as shown in Fig. 2(a).

However, it is limited that only one direction can be collimated by using this method. Based on this design, a design has been reported using two hyperboloid cylinder-plane lenses arranged perpendicularly to collimate both the fast and the slow axial directions [8], as shown in Fig. 2(b). In addition, this kind of design is suitable to use for linear light source.

Otherwise, there are also some kinds of good methods for laser beam shaping discussed by scientists, for example, Serkan and Kirkici had presented two optical system designs using aspherical lenses for beam circularization, collimation and expansion of semiconductor lasers [9].

Because of the requirement of differing application requirements, no single beam shaping method is suitable for all situations. Specific laser beam shaping systems need to be developed for specific applications. When used in the practical industrial and commercial manufacture, both of the methods mentioned above have difficulty shaping the diode beams appropriately and being packaged in small volume.

The purpose of this paper is to discuss a method for semiconductor lasers beam shaping by putting the lasers into an aspheric lens, so that the divergence angle of the laser beam can be reduced effectively and the LD is packaged at the same time. That makes the package of the LD small and low-cost.

2. Optical model design

The optical model is shown in Fig. 3. Since the light source is a point, and this beam shaping method is independent of divergence angle, the ellipsoidal shape in the fast-axial and the slow-axial direction should be the same, so only one direction is discussed here.

The semiconductor laser is packaged in an aspheric lens, which is made from epoxy resin or optical glass. This structure is axisymmetric, and the irradiance is emitted from the aspheric side. The package can be produced right after the laser diode is

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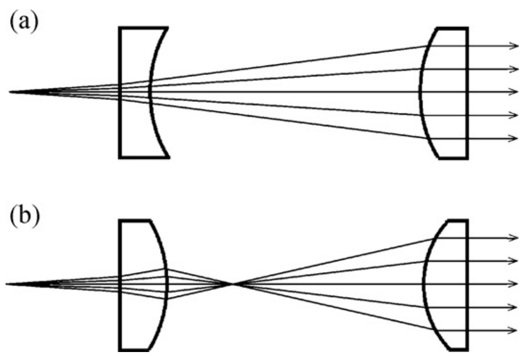

Fig. 1. Plano-aspheric lens pair used for beam shaping.

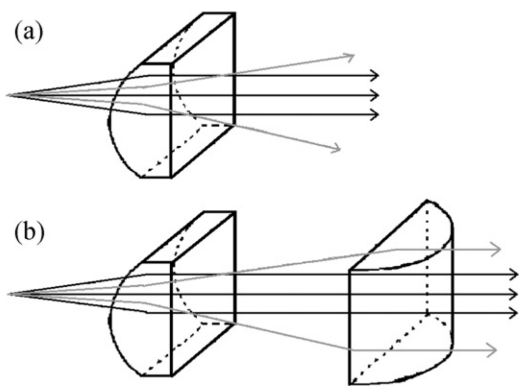

Fig. 2. Hyperboloid lens used for beam shaping.

manufactured, so the laser diode does not need to be encapsulated any more. In this structure, the laser beam is emitted directly into the materials like epoxy resin or optical glass (we use epoxy resin in our experiment), whose refractive index is higher than that of air. When the beam reaches the aspheric side and enters the air, the rays become parallel.

The light is emitted from a small source point and transformed in the epoxy resin. Semiconductor lasers have Gaussian irradiance profiles, and their divergence angles are approximately 30° in the fast axial direction and 15° in the slow axial direction. To improve the beam quality, the surface of the lens needs to be designed to refract the rays parallel to the x-axis so they form a parallel beam with a small divergence angle. The shape of the refractive surface of the designed lens can be determined by numerical analysis, but the related constants, such as the refractive index, should be determined first, and then we can calculate the radian of the ellipse.

According to Fermat's principle, all the optical paths of any refracted rays from source to target plane should be equal. Here, the light source is supposed to lie in the origin of axis, $M(x, y)$ is any point on the lens, the parameter l is the length between origin and the apex of the lens, as shown in Fig. 4.

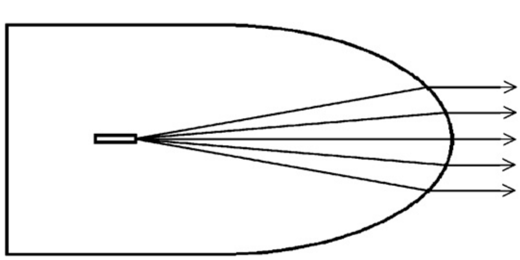

Fig. 3. Aspheric lens model used for beam shaping.

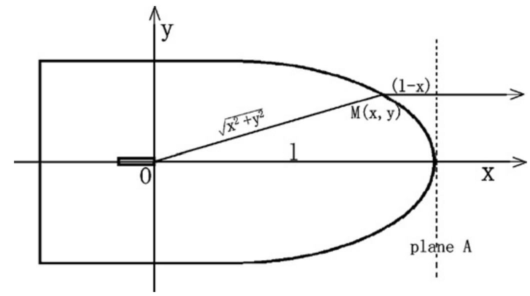

Fig. 4. Two of the optical paths in the shaping system.

Then the equation about the two rays in Fig. 4 is

$$nl = n\sqrt{x^2+y^2} + n_0(l-x) \tag{1}$$

Here, n and n_0 are the refractive indexes for the interior material and exterior material respectively ($n_0 = 1$ in this paper). The equation above can be reduced to

$$nl - l + x = n\sqrt{x^2+y^2} \tag{2}$$

where n and l are defined as

$$n = \frac{a}{c} \tag{3}$$

$$l = a + c \tag{4}$$

The equation above can be rewritten like this

$$a^2 - c^2 + xc = a\sqrt{x^2+y^2} \tag{5}$$

Square both sides of the equation

$$\frac{(x-c)^2}{a^2} + \frac{y^2}{a^2-c^2} = 1 \tag{6}$$

This is the equation of an ellipse, where the long axis is equal to a, and the short axis is

$$b = \sqrt{a^2-c^2} \tag{7}$$

The shape of the aspheric lens is an ellipsoid and the laser lies in one of its foci, as shown in Fig. 5.

Since the refractive index of the epoxy resin is known, the shape of the ellipse can be calculated. From the equations above, one parameter of the ellipse equation must be known first; that means "a" or "b" or "c" should be determined before starting the calculation. In this paper, "b" is known. In this condition, Eqs. (3) and (7) become

$$a = \frac{bn}{\sqrt{n^2-1}} \tag{8}$$

$$c = \frac{b}{\sqrt{n^2-1}} \tag{9}$$

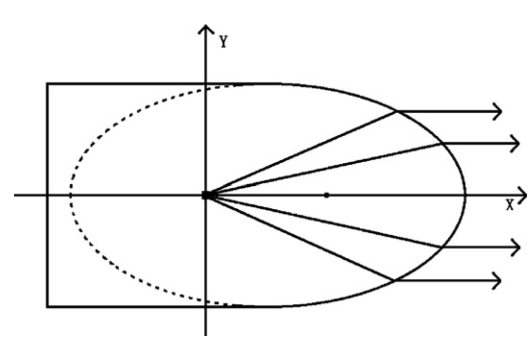

Fig. 5. Optical path of a bundle of rays through the ellipsoidal lens.

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