The elliptical micro-lens array in the application of the LDA beam shaping

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A B S T R A C T

Based on the analysis of semiconductor laser-diode array (LDA) beam characteristics, a new scheme of beam collimation and focusing is proposed. The elliptical micro-lens shaping the beam of LDA has been analyzed by theoretical and simulated by optical ray tracing. The efficiency for laser beam coupling into the optical fiber is 73.2% of the whole system.

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1. Introduction

High-power laser-diode array stacks have a growing number of applications in areas such as materials processing, pumped solid-state lasers, laser medical and military [1,2]. Their application potential is derived from one or more of their unique properties which include high-conversion efficiency, small size, light weight and long lifetime. However, LDA of bedding face, big divergence angle, astigmatism (fast axis direction is 36–40° half peak width and the slow axis of 8–10° half peak width as shown in Fig. 1) characteristics have become the bottleneck of its application. So far, the high-power LDA coupling mainly adopts two technical routes: fiber bundle coupling method and micro-optics system coupling method [3,4]. The latter has good beam uniformity, high efficiency of plastic, compact structure, is the most popular approach to the current diode laser beam shaping [5].

As shown in Fig. 2, the whole collimation and focusing system consists of elliptical micro-lens array, gradient index lens and focusing lens in three parts. First, the numerical analysis and design of the elliptic lens are proposed in Section 2. In Section 3, the influence of oblique incidence on the fiber coupling efficiency is analyzed. Optical ray tracing simulation is also made to calculate coupling efficiency. The whole system is used to improve the coupling efficiency and reduce the processing cost.

2. Numerical analysis and ray tracing simulation

Fig. 3 shows the model of the collimating lens. $n_0$ and $n_1$ represent the refractive index of space and lens material respectively, $f$ is the focal length of the lens, $d$ is the thickness of the lens, $D$ is the clear aperture of the lens, $l$ is one of the off-axis light which intersects the lens at $Q(x,y)$.

By Fermat’s principle, the off-axis light and axis light should be satisfied by

$$n_0 l = n_0 f + n_1 l$$  \hspace{1cm} (1)

For the off-axis light

$$I = \frac{f + x}{\cos \alpha}$$  \hspace{1cm} (2)

By Eqs. (1) and (2), the following relationship can be obtained

$$x = \frac{n_0 f (1 - \cos \alpha)}{n_1 \cos \alpha - n_0}$$  \hspace{1cm} (3)

By the geometric relationship we obtain

$$y = (f + x) \tan \alpha = \frac{(n_1 - n_0) f \sin \alpha}{n_1 \cos \alpha - n_0}$$  \hspace{1cm} (4)

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For Eqs. (3) and (4), it can be written as
\[
\frac{(x + \frac{n_0}{n_1 + n_0})^2}{\left(n_0f/n_1 + n_0\right)^2} - \frac{y^2}{f^2 \left(n_1 - n_0/n_1 + n_0\right)} = 1
\]  
(5)

By setting
\[
a = \frac{n_0}{n_1 + n_0}, \quad b = f \sqrt{\frac{n_1 - n_0}{n_1 + n_0}}, \quad e = \frac{n_1}{n_0}
\]  
(6)
Eq. (5) can be written as
\[
\frac{(x + a)^2}{a^2} - \frac{y^2}{b^2e} = 1
\]  
(7)

Obviously, the plano-convex lens is a typical hyperbola surface. Any type of lens similar to the hyperbolic lens can play a good effect in the proposed system. But it is with difficulties to be processed into micro-lens by conventional fabrication process. The fabrication of micro-lens using droplet-on-demand inkjet method has attracted considerable attention because of the potential applicability to micro-optical system, especially for ellipse-like surface type [6]. In the following work, the ellipse surface is designed to approximate the hyperbola type, and the collimating effect of hyperbolic lens and elliptic lens will be compared.

The elliptical equation is
\[
\frac{(x_1 - a_1)^2}{a_1^2} + \frac{y^2}{b_1^2} = 1
\]  
(8)

While doing the calculations, \(n_1 = 1.52\), \(n_0 = 1\), \(f = 0.5\) mm. In Eqs. (5) and (6), we get \(a = 0.1984\) mm, \(b = 0.2271\) mm. Assume that the divergence angle of the light is 40°, in Eqs. (3) and (4), let \(\alpha = 20°\), we get \(y = 0.2076\) mm, \(x = 0.0704\) mm. As the length of the elliptical axis, \(a_1 = 0.0704\) mm, \(b_1 = 0.2076\) mm. Fig. 4(a) shows the hyperbolic curve and the elliptic curve. The optimism parameters of short and long axis of elliptic curve are \(a_1 = 0.2004\) mm and \(b_1 = 0.2676\) mm. Fig. 4(b) shows the elliptic curve is very close to ideal hyperbolic. It is can be seen that the elliptical lens can be used in semiconductor laser collimation system.

Based on Ze-max simulation software, some ray tracing simulations are made for elliptical and hyperbolic type surface [7,8].
Table 1
The key parameters of hyperbolic and elliptic lens.

<table>
<thead>
<tr>
<th>Type</th>
<th>a(α₁)</th>
<th>b(β₁)</th>
<th>Thickness</th>
<th>f</th>
<th>Conic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hyperbolic</td>
<td>0.1984</td>
<td>0.2271</td>
<td>0.1082</td>
<td>0.5</td>
<td>-2.3104</td>
</tr>
<tr>
<td>Elliptic</td>
<td>0.2004</td>
<td>0.2676</td>
<td>0.1082</td>
<td>0.5</td>
<td>0.783</td>
</tr>
</tbody>
</table>

Fig. 5. Ray tracing simulation of the hyperbolic and elliptic lens. (a) Hyperbolic lens. (b) Elliptic lens.

The key parameters of hyperbolic and elliptic curve are shown in Table 1.

Fig. 5(a) and (b) shows the ray tracing simulation for the hyperbolic and elliptic lens. It is shown that the hyperbolic lens has a perfect effect of collimation. And the collimation effect of the elliptic lens is very close to that of the hyperbolic lens.

In order to make lights out of elliptic lens more parallel, a gradient index lens is designed behind the micro-lens array (as shown in Fig. 2), the thickness of the gradient index lens is 0.1 mm and the central refraction index is n0 = 1.52, the refraction index difference is Δn = −0.12.

3. Analysis and calculation of the coupling efficiency

In the proposed system, an inverse plano-convex lens is used to focusing the collimating light transmitted from the micro-lens array. The plano-convex lens has been proved before as shown in Eqs. (6) and (7), Section 2. The key parameters of focusing lens as shown in Table 2.

Indeed, diode beam collimated by elliptical lens is not parallel, which lead to the lights out of the focusing lens are a serials of spots. In the oblique incidence situation [9], spot closer to the edge of the coupling lens would have a bigger incident angle, therefore will lead to lower coupling efficiency. Fig. 6 shows the edge of the light spot coupled into the fiber. Where, n0 and n1 represent the refractive index of space and lens material respectively, n2 represents the refractive index of cladding. Δφ is the tilt angle of incident lights, w is the waist radius of the focal beam.

In the case of alignment, the coupling efficiency is [10]

$$\eta = \frac{\int \int |E_{i,b}^2| ds \times \int \int |E_{f,b}^2| ds}{\int \int |E_{i,a}^2| ds \times \int \int |E_{f,a}^2| ds}$$

where $E_{i,b}$ represents incident light field of focal plane, $E_{f,b}$ represents the electric field of the optical fiber, integral is made on whole focal plane.

By Parseval theorem, Eq. (9) can be written as

$$\eta = \frac{\int \int |E_{i,a}^2| ds \times \int \int |E_{f,a}^2| ds}{\int \int |E_{i,a}^2| ds \times \int \int |E_{f,a}^2| ds}$$

where $E_{i,a}$ represents incident light field of receiving aperture plane, integral is made on whole receiving aperture plane. Considering the incident wave is an ideal plane wave, Eq. (10) can be simplified to

$$\eta = \frac{2 \left[ 1 - \exp \left(-\beta^2 \right) \right]^2}{\beta^2}$$

where $\beta = \pi R_0 \omega_0 / (\lambda f)$ represents the coupling coefficient. $R_0$ is the radius of the optical receive aperture, $\omega_0$ is fiber mode field radius, $\lambda$ is incident wavelength, $f$ is focal length of coupling lens. While $\beta = 1.12$, coupling efficiency maximum is 81.45%.

While the incident lights have a tilt angle $\Delta \phi$, the coupling efficiency is

$$\eta_{\Delta \phi} = 8 \beta^2 \exp \left(-2\gamma^2 \Delta \phi \right) \left[ \frac{1}{R^2} \int_0^R \exp \left(-\frac{\beta^2 r^2}{R^2} \right) I_0 \left(\frac{2\gamma \Delta \phi \beta}{R} \right) r \, dr \right]$$

where $I_0$ is the Bessel function of the first kind of zero order, $\gamma = \Delta \phi / \lambda$, $\beta = 1.12$. In single-mode fiber, Eq. (12) can be approximated as

$$\eta_{\Delta \phi} \approx 0.8145 \exp \left[ \frac{\pi \times \Delta \phi \omega_0}{\lambda} \right]$$

Fig. 7 shows the influence of incident angle on the fiber coupling efficiency. Multi-mode fiber has a similar conclusion.

Since each of exit spot intensity is similar to Gaussian distribution, we suspect that optical fiber with spherical end face (micro-lens) can reduce the incident light angle of the central part of the light spot and improve the coupling efficiency (as shown in Fig. 6, the dotted line). The key parameters of micro-lens at the end of the fiber are as shown in Table 3.

Fig. 8 shows the beam collimated through elliptical micro-lens coupled into the optical fiber, thirteen diodes (with one-watt power)
power) are used as light source, total power of the light source is 13 W. The optical fiber with micro-lens is shown in the inset of Fig. 8(b) and (c). The system with gradient index lens is shown in Fig. 8(c). Fig. 9(a)–(c) represent the illumination distribution in the situation of Fig. 8(a)–(c), respectively. At the bottom of each picture shows the received energy. For Fig. 8(a), the coupling efficiency is \((8.7484/13) \times 100\% = 67.3\%\). For Fig. 8(b), the coupling efficiency is \((9.0685/13) \times 100\% = 69.76\%\). For Fig. 8(c), the coupling efficiency is \((9.5202/13) \times 100\% = 73.2\%\). Hence gradient index lens make lights out of elliptic lens more parallel and improve the coupling efficiency of 3.44\%, the fiber with spherical end face can improve the coupling efficiency of 2.46\%.

**4. Conclusion**

Elliptic curve which approximation the hyperbolic curve have a good effect of collimating LDA beam. The elliptical micro-lens shaping the beam of LDA has been analyzed by theoretical and simulated by ray tracing. Gradient index lens make lights out of elliptic lens more parallel and improve the coupling efficiency of 3.44\%.
fiber with spherical end face can improve the coupling efficiency of 2.46%. The efficiency for laser beam coupling into the optical fiber can be achieved 73.2%.

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