Shaping Semiconductor Laser Beam with One-Dimension Gradient-Index Lens

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Abstract. This paper’s main purpose is collimating, shaping and coupling semi-conductor laser beam by one-dimension gradient-index lens with parabolic-index profiles along the direction of thickness has been fabricated by ion-exchanging process. Introduced the ray matrix equation of One-dimension gradient-index lens and formation process of parabolic-index profiles. Measured distribution constant of refraction in varied thickness. Using one-dimension gradient-index lens with varied thickness replacing cylindrical lens collimating, shaping and coupling semi-conductor laser beam. Using two perpendicular one-dimension gradient-index lens shaping laser beam by two direction. Maked a mini and new semiconductor laser coupler. Demonstrated a coupling efficiency of 80\% which from semi-conductor laser beam into single-mode fiber.

1. Introduction
Semiconductor lasers have become very important components for modern communication system, medical system, military. However, the highly elliptical output beam of the emitted laser light is a serious problem for the design of collimation lens systems. The full diverging angle of emitted light of a laser diode in direction of the diode junction, the fast axis, is typically 30–60°. Therefore all current techniques for beam shaping start with collimating the radiation in the direction of the fast axis. For this collimation there is a need for cylindrical microlenses with a numerical aperture(N.A.) of at least 0.5 [1].

One dimension GRIN lens [2] are produced by realization of a one dimensional refractive-index profile perpendicular to the optical axis. This is done by exchanging ions through the surfaces of a slab of glass and cutting the slab to lenses. One dimension GRIN lens are an advantageous alternative because they are suitable for mass production and are characterized by large alignment tolerances resulting from their isoplanatic performance. The highest N.A. can be obtained by use of the maximum difference of refractive index achievable in the glass (with the present technique of ion exchange, the maximum $\Delta n$ is 0.1).

The lasers with a large aspect ratio will result in a poor coupling efficiency when the light is coupled to a single mode fiber by using the conventional optical design. The larger the aspect ratio is, the more degradation in the coupling efficiency will be.
In this paper we present the design and the optical modeling of a cruciform one dimension GRIN lens to replace the corrective lens in the laser diode beam shaping system and demonstrate a coupling efficiency of 80%. We make a mini and new semiconductor laser coupler.

2. Fabrication of one dimension GRIN lens
We produced one dimension GRIN lens varied thickness from 200um to 2000um by Tl ion exchange in glass. As shown schematically in Figure 1.

![Figure 1. refractive-index profile of one dimension GRIN lens.](image)

The parameter of one dimension GRIN lens is shown in table 1:

| Thickness(mm) | Wavelength(nm) | Focus constant $\sqrt{A}$(mm$^{-1}$) | Center refractive index $n_0$ | numerical aperture |
|---------------|----------------|-------------------------------------|-----------------------------|-------------------|
| 2             | 1550           | 0.3661                              | 1.635                       | 0.6               |
| 1.26          | 1550           | 0.674                               | 1.5910                      | 0.46              |
| 0.5           | 1550           | 1.14                                | 1.5910                      | 0.46              |
| 0.3           | 1550           | 2.618                               | 1.635                       | 0.6               |

one dimension GRIN lens with a parabolic index profile such as

$$n(x) = n_0 \left(1 - \frac{1}{2}Ax^2\right)$$  \hspace{1cm} (1)

Where $n_0$ is the refractive index on the center surface, $x$ is the distance from the center surface, and $\sqrt{A}$ is the focusing factor.

![Figure 2. ray path through lens by x and y direction.](image)

As shown in figure 2, ray path through lens by x and y direction is different. In the x direction, ray path through lens on sinusoid, but in the y direction, ray path through lens in a beeline.

Ray path through x direction of lens of ray matrix equation can be expressed as
\[
\begin{bmatrix}
    x \\
    p
\end{bmatrix} = \begin{pmatrix}
    \cos(\sqrt{A}z) & \frac{1}{\sqrt{A}} \sin(\sqrt{A}z) \\
    -\sqrt{A} \sin(\sqrt{A}z) & \cos(\sqrt{A}z)
\end{pmatrix} \begin{bmatrix}
    x_0 \\
    p_0
\end{bmatrix}
\]

As shown in equation (2), if we get position \(x_0\) and slope \(p_0\), we can calculate ray path through x direction of lens.

3. Collimating semiconductor laser beam with one-dimension gradient-index lens [3]

The laser diode beam is divergent in both parallel and perpendicular direction. The aspect ratio of laser beam is typically 4.25:1. The elliptical beam of a laser can be collimated by a pair cruciform of one-dimension gradient-index lenses, as shown in figure 3. In this scheme the first one-dimension gradient-index lens has the responsibility of collimating the beam along its fast divergence axis, while the second one-dimension gradient-index lens collimate the beam along its slow axis. The first lens is the key lens to correction the aspect and reduce the astigmatism.

![Figure 3](image-url)  
Figure 3. Laser beam collimated by a pair of one-dimension GRIN lenses.

As a concrete example, consider a laser beam having \(\lambda=808\text{nm}, \theta_\|=34^\circ, \theta_\perp=8^\circ\). We simulated laser beam collimating by a pair cruciform one dimension GRIN lenses with ZEMAX.

A good optical shaping system should achieve two performances. First, the fast axis and slow axis divergence angle both should be collimated. Second, the aspect ratio of laser beam should be shaped to 1.

The first one dimension GRIN lens is collimating fast axis. We should using lens with high Focus constant \(\sqrt{A}\) to compressing the fast axis high angle for matching the slow axis divergence angle. So, the thickness of first lens is 0.5mm, \(\sqrt{A}\) is 1.14 mm\(^{-1}\). Length of first lens is \(Z1=0.8\text{mm}\). The work distance between the front facet of the laser and the first surface of this lens is 0.4mm. The thickness of second lens is 2mm and \(\sqrt{A}\) is 0.3661 mm\(^{-1}\). The second lens is separated by 0.8mm from the first lens. Length of second lens is \(Z2=1.5\text{mm}\). As shown in Figure 4.

![Figure 4](image-url)  
Figure 4. Ray tracing laser beam collimated by a pair Cruciform one-dimension GRIN lenses.
The beam pattern at the output of the systems is near circular with mode field radius of 201μm in x axis and 198μm in y axis. The aspect ratio of output beam is 1.01, it's very close to 1. The fast axis and slow axis angle both be collimated to 0.01° which is very close to 0°.

4. Coupling laser beam in single mode fiber

We can prominently improve laser beam coupling efficiency by using a pair cruciform of one dimension gradient-index lenses [4,5]. First, laser beam were collimated by a pair one dimension GRIN lenses. Second, the collimated laser beam were coupled in a single mode fiber by a GRIN rod lens. As shown in Figure 5.

The first design simulated with ZEMAX. As shown in figure 6. Fast axis lens is ZGR1, length is z1=2.2mm, slow axis lens is ZGR2, length is z2=1.2mm. The thickness of ZGR1 and ZGR2 are 2mm. The work distance is 1.5mm. The third lens is GRIN rod lens which can focusing beam. The lens's length is z3=4.5mm. The output beam pattern of fast axis is collimated with mode field radius of 660μm. The output beam pattern of slow axis is collimated with mode field radius of 260μm. The aspect ratio of output beam is 2.5. Laser beam of fast axis focused to spot with RMS radius 25μm. Laser beam of slow axis focused to spot with RMS radius 0.8μm. The coupling efficiency of fast axis is \( \eta_f = 14\% \), the coupling efficiency of fast axis is \( \eta_s = 77\% \). The coupling efficiency of system is

\[
\eta_1 = \sqrt{\eta_f} \times \sqrt{\eta_s} = 33\%.
\]

We made a mini LD coupler by the first design. The coupling efficiency of laser diode couple in multi-mode fiber is 60%. As shown in figure 7. Because it can receive high divergence angle and it is easy to mount. It work distance is 1.5mm. It can be widely used in To-packaged laser diode with protect protecting glass. This work distance of shaping system must be longer than 1mm. The LD coupler can be mass produced.
Figure 7. LD coupler.

For improving coupling efficiency, we used shaping optical design in Section 3. As shown in figure 8. The thickness of first lens is 0.5mm. Length of first lens is Z1=0.8mm. The work distance is 0.4mm. The thickness of second lens is 2mm. Length of second lens is Z2=1.5mm. The second lens is separated by 0.8mm from the first lens. The third lens is GRIN rod lens which can focusing beam. The lens’s length is z3=4.5mm. The output beam pattern of fast axis is collimated with mode field radius of 201um. The output beam pattern of slow axis is collimated with mode field radius of 198μm. The aspect ratio of output beam is 1.01. Laser beam of fast axis focused to spot with RMS radius 13um. Laser beam of slow axis focused to spot with RMS radius 0.5um. The coupling efficiency of fast axis is ηi=79%, the coupling efficiency of fast axis is ηi=80%. The coupling efficiency of system is ηi=√ηi ×√ηi=80%

(a) fast axis coupling
(b) slow axis coupling

Figure 8. second design simulated coupling with ZEMAX.

5. Conclusion
We produced one dimension gradient-index lens varied thickness from 200um to 2000um by Tl ion exchange in glass. We have designed one-dimension gradient-index lens with varied thickness replacing cylindrical lens collimating semi-conductor laser beam. We have designed and simulated the performance of a laser beam shaping system with a pair cruciform one-dimension gradient-index lens. Maked a mini and new semiconductor laser coupler. Demonstrated a coupling efficiency of 80% which from semi-conductor laser beam into single-mode fiber.

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