Optimal distance from high power laser diode to cylindrical microlens in a coupling system

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In a practical coupling system, a cylindrical microlens is used to collimate the emission of a high power laser diode (LD) in the dimension perpendicular to the junction plane. Using passive alignment, the LD is placed in the focus of the cylindrical microlens generally, regardless of the performance of the multimode optical fiber and the LD. In this paper, a more complete analysis is arrived at by ray-tracing technique, by which the angle θ of the ray after refraction is computed as a function of the angle θ_0 of the ray before refraction. The focus of the cylindrical microlens is not always the optimal position of the LD. In fact, in order to achieve a higher coupling efficiency, the optimal distance from the LD to the cylindrical microlens is dependent on not only the radius R and the index of refraction n of the cylindrical microlens, but also the divergence angle of the LD in the dimension perpendicular to the junction plane and the numerical aperture (NA) of the multimode optical fiber. The results of this discussion are in good agreement with experimental results.

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High power laser diodes have expanded their roles in many fields because of their higher conversion efficiencies from electrical to optical powers, as well as their lower costs than competing gas or solid-state laser systems and their mass production potential. In many practical applications such as medicine, materials processing, solid-state laser end-pumping, industry and aerospace, it is often necessary to couple the light from LD into multimode optical fiber[1−3].

It is well-known that the far-field pattern of a LD exhibits a relatively close resemblance to Gaussians. The cross section of the beam is elliptical[4,5]. The beam divergence angle $\theta_\perp$ (measured at the $1/e^2$ intensity points) is about 40° in the dimension perpendicular to the junction (fast axis), but in the dimension parallel to the junction (slow axis), it is about 6°.

In many practical coupling systems, with passive alignment a piece of optical fiber is often used as an inexpensive cylindrical microlens to collimate the emission of a LD in fast axis[6]. The LD is placed in the focus of the cylindrical microlens generally. The focal length of the cylindrical microlens may be determined by

$$f = nR/[2(n-1)], \tag{1}$$

where f is the focal length of the microlens, n and R are the index of refraction and the radius of the cylindrical microlens, respectively. Thus the optimal distance from the LD to the microlens surface is

$$d_0 = R(2-n)/[2(n-1)]. \tag{2}$$

In fact, in order to achieve a higher coupling efficiency, the optimal distance from the LD to the cylindrical microlens is dependent on not only the radius and the index of refraction of the cylindrical microlens, but also the divergence angle of the LD in fast axis and the numerical aperture of the multimode optical fiber. In this paper a more complete analysis is arrived at by ray-tracing technique, by which the angle θ of the ray after refraction is computed as a function of the angle θ_0 of the ray before refraction. This discussion is demonstrated with coupling a LD into a multimode optical fiber.

The geometry of the situation is indicated in Fig. 1 together with an incident ray FA, which intersects the spherical surface at A. This ray is refracted finally at an angle θ relative to the axis of the cylindrical microlens. There are, in fact, two distinct mechanisms by which a ray may not be coupled into the multimode optical fiber core: (1) If the angle after refraction, θ, is greater in magnitude than the critical angle $\theta_c = \arcsin\sqrt{n_1^2 - n_2^2}$ for total internal reflection at the core-cladding interface; (2) If the ray angle θ_0 is greater than the maximum acceptance angle of the microlens $\theta_{\max} = \arcsin\left(\frac{1}{1+d/R}\right)$, the ray will miss both the cylindrical microlens and the multimode fiber.

By ray-tracing technique, θ is given by

$$\theta = \theta_0 + 2[\arcsin\left(\frac{d+R}{R}\cdot\sin\theta_0\right) - \arcsin\left(\frac{d+R}{nR}\cdot\sin\theta_0\right) - \theta_0], \tag{3}$$

where d is the distance from the LD to the microlens surface, R is the radius, and n is the index of refraction of the cylindrical microlens.

If we have $n = 1.45$ and $R = 70$ μm for a cylindrical microlens, the angle θ of the ray after refraction is computed as a function of the angle θ_0 of the ray before refraction. The results of such a calculation are shown in Fig. 2, each curve giving the angle transformation $\theta(\theta_0)$ for a different LD-lens spacing. It is seen that for each small d presented, the rays diverge ($\theta < 0$) for small θ_0, which then converge for somewhat larger θ. Each curve for $\theta(\theta_0)$ reaches a minimum θ, which may or may not be within the range for total internal reflection. For larger d, it is seen that the rays diverge ($\theta > 0$) continuously.

If the angle θ is less than the critical angle for total

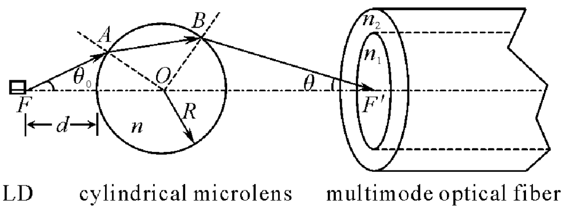


Fig. 1. Schematic diagram of a coupling system using a cylindrical microlens.

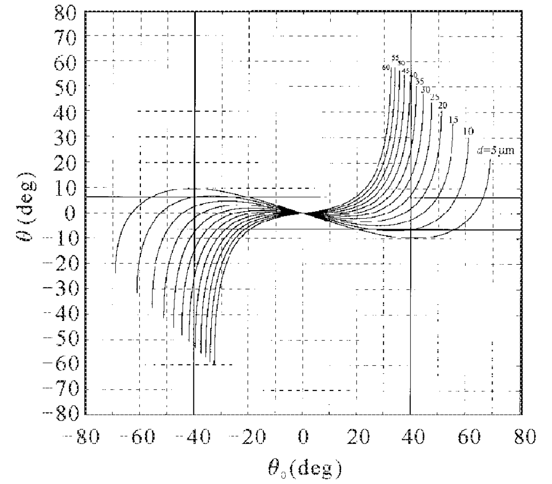


Fig. 2. The angle θ of the ray after refraction versus the angle θ_0 of the ray before refraction.

internal reflection θ_c, the ray will be trapped in the multimode fiber core. The larger the distance d from the LD to the microlens surface, the smaller the θ_0. However, the larger the distance d, the smaller the maximum acceptance angle of the microlens. So in order to achieve a higher coupling efficiency, the beam divergence angle of the LD in fast axis and the NA of the multimode fiber must be considered.

The procedure for using the results of Fig. 2 to determine the optimal distance from the LD to the microlens surface is as follows. The critical angle for total internal reflection of the multimode optical fiber θ_c is first calculated and horizontal lines $\theta = \pm\theta_c$ are laid out in Fig. 2. Only rays having $|\theta(\theta_0)| \leq \theta_c$ will be accepted into the core of the fiber. Then according to the divergence angle of the LD in fast axis, the optimal distance can be achieved.

As an example, if the NA of the multimode fiber is 0.11, then the critical angle for total internal reflection $\theta_c = 6.3°$. The $|\theta|$ should not be greater than 6.3°. In a practical coupling system in which a cylindrical If the divergence angle $\theta_\perp$ of the LD is 40° (measured at the $1/e^2$ intensity points), the optimal distance is within $12-23$ μm. As a comparison, Eq. (2) predicts In a practical coupling system in which a cylindrical the optimal distance $d_0 = 42.8$ μm, regardless of the NA of the multimode fiber and the divergence angle $\theta_\perp$ of the LD.

The LD ($\theta_\perp = 40°$ which is measured at the $1/e^2$ intensity points, $\lambda = 808$ nm), the cylindrical microlens (a piece of multimode optical fiber having $n = 1.45$, $R = 70$ μm) and the multimode optical fiber (NA = 0.11) are mounted on separate five-dimensional micromanipulators. The normalized coupling efficiency versus the distance from the LD to the cylindrical microlens is shown in Fig. 3. In focus where $d = 42.8$ μm, the coupling efficiency is lower than that of $d = 20$ μm. The difference between them is about 5%, which is approximately equal to the loss of Fresnel reflection. The observed coupling efficiencies are in good agreement with theoretic results.

Figure 4 shows the photographs of LD's optical spots. In Fig. 4(a), the output radiation produced by the LD, is highly divergent in fast axis. As shown in Figs. 4(b) and (c), after collimated, most of the emission of the LD is focused in a rectangular region which can be named "power center". There is still some ambient power around it. It can be seen that the power center of $d = 20$ μm is wider than that of $d = 40$ μm, but the ambient power of the former is obviously less than that of the latter. When the distance is increased from 20 to 40 μm, the width of the power center is decreased continuously. At the same time, the ambient power is strengthened gradually. The collimated spot of $d = 20$ μm is more resemble to a round spot. Thus the coupling efficiency of $d = 20$ μm is higher than that of $d = 40$ μm where it is in focus. Therefore, Fig. 4 also confirms the theory above.

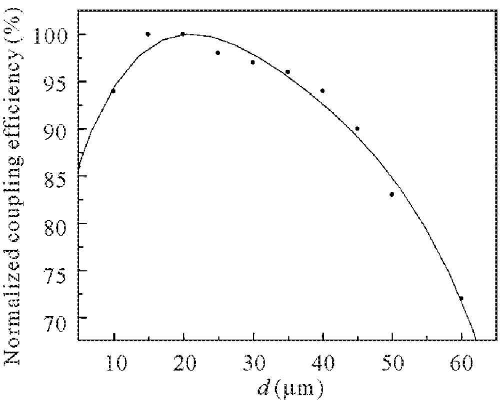
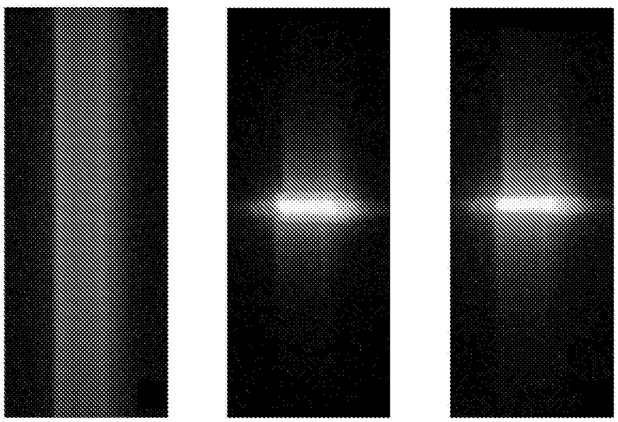


Fig. 3. The normalized coupling efficiency versus the distance from the LD to the cylindrical microlens.



(a) (b) (c)

Fig. 4. Photographs of LD's optical spot. (a) LD's spot before collimation. (b) Collimated spot of $d = 20$ μm. (c) Collimated spot of $d = 40$ μm .

In a practical coupling system in which a cylindrical microlens is used to collimate the emission of a LD in fast axis, the focus of the cylindrical microlens is not always the most suitable position for the LD. The optimal distance from the LD to the cylindrical microlens is dependent on not only the radius R and the index of refraction n, but also the performance of the multimode optical fiber and the LD. In order to achieve a higher coupling efficiency, the beam divergence angle of the LD in fast axis and the NA of the multimode optical fiber must be also considered.

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References

1. C. Q. Wang, Y. T. Chow, L. Reekie, W. A. Gambling, H. J. Zhang, L. Zhu, and X. L. Meng, Appl. Phys. B **70,** 769 (2000).
2. T. Kasamatsu, T. Sumiyoshi, and H. Sekita, Appl. Phys. B **69,** 491 (1999).
3. S. Taccheo, P. Laporta, S. Longhi, O. Svelto, and C. Svelto, Appl. Phys. B **63,** 425 (1996).
4. S. Nemoto, Appl. Opt. **33,** 6387 (1994).
5. Y. Li and J. Katz, Appl. Opt. **35,** 1442 (1996).
6. Head *et al.*, "Apparatus for coupling a multiple emitter laser diode to a multimode optical fiber," U.S.patent 5,436,990 (July 25, 1995).