

Design of a Tapered Lens for Semiconductor Laser to Single-Mode Fiber Coupling

Ma Yan and Xie Fuzeng

(Institute of Semiconductors, The Chinese Academy of Sciences, Beijing 100083, China)

Abstract: The theoretical investigation of the coupling efficiency of a laser diode to a single mode fiber via a hemispherical lens on the tip of the tapered fiber in the presence of possible transverse offset and angular mismatch is reported. Without the misalignment, coupling efficiency increases with the decreasing of taper length. With the misalignment, this relation is that the coupling efficiency decreases with each kind of offset.

Key words: high bit-rate communication; fiber coupling; tapered lens; offset

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1 Introduction

Efficient coupling between a laser diode (LD) and a single-mode fiber (SMF) is essential for many applications such as in low loss, high bit-rate communication systems. Their small core sizes, however, require highly precise alignment in a splice and in power coupling from light sources. A simple butt joint method gives poor coupling efficiency, typically on the order of 10 percent because of mismatch of the semiconductor laser and single-mode fiber modal profiles (spot sizes). Elaborate experiments have been performed to improve the coupling efficiency. Today a compact and low-loss coupling between LD and SMF is a basic, important technical aspect in the construction of practical fiber networks. Lensed fibers have features that are suitable for the coupling, such as compactness, simplicity, stability, and freedom from bulky lenses. Several lensed fiber techniques have been proposed to improve the coupling efficiency and amongst the techniques used are conically ended fiber, tapered ended fiber, hemispherical ended fiber and wedge

ended fiber^[1-4]. Among these methods, design of a hemispherical lens tipped onto a tapered SMF is most promising because of its relative ease of fabrication, reasonable coupling efficiency, and reduced harmful back-reflected light into the laser diode^[5-7].

The purpose of this paper is to provide a method for designing a coupling hemispherical lens tipped onto a tapered SMF, and verify it using experiment results. Optimum lens radius of curvature, optimum interval between laser and fiber, maximum coupling efficiency, and misalignment effects are discussed.

2 Theoretical analysis and experimental verification

A basic coupling scheme between LD to tapered lensed SMF is shown in Fig. 1. Our analysis contains some usual approximations^[8], namely no loss for transmission, Gaussian field distributions for both the source and the fiber, perfect matching of the polarization of the field of the fiber and that on the lens surface and finally angular width of the

lens large enough to intercept the entire power radiated by the source for typical values of lens parameters used here. Further, the distance between the laser diode and the nearest point of the tapered lens is kept equal to the focal length of the lens for no spherical aberration^[8,9]. The coupling of field in the tapered region of fiber occurs only from the core-guided mode to the fundamental cladding-guided mode.

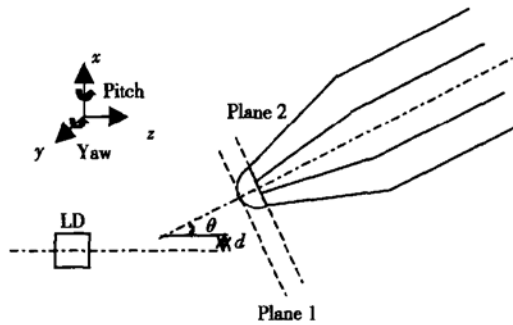


Fig. 1 Schematic diagram of LD to SMF coupling configuration via a lensed taper

2.1 Coupling without misalignment

Firstly we analyse the situation of no misalignment ($d = 0, \theta = 0$). The field ψ_u of the output of the laser diode at a distance u from the LD surface can be given as follow^[10]:

$$\psi_u = \exp\left[-\left(\frac{x^2}{w_{1x}^2} + \frac{y^2}{w_{1y}^2}\right)\right] \exp\left[-jk_1\left(\frac{x^2}{2R_{1x}} + \frac{y^2}{2R_{1y}}\right)\right] \tag{1}$$

where w_{1x} and w_{1y} are the spot sizes along two perpendicular directions x and y , R_{1i} is the radius of curvature of the wavefront from the laser source and k_1 is the wave number in the incident medium (now mentioning as free space),

$$w_{1i}^2 = w_{i0}^2 \left[1 + \left(\frac{2z}{k_1 w_{i0}^2}\right)^2\right]$$

$$R_{1i} = z \left[1 + \left(\frac{k_1 w_{i0}^2}{2z}\right)^2\right]$$

while w_{i0} denotes the waist spot sizes in the $x-z$ and $y-z$ plane.

We also express the fundamental mode in the circular core fiber as^[10]

$$\psi_t = \exp\left[-(x^2 + y^2)/w_t^2\right] \tag{2}$$

where the spot size is approximated as^[11]

$$w_t = a[0.65 + 1.619/V^{1.5} + 2.879/V^6] \tag{3}$$

here a is the core radius and V is the normallized frequency given by $V = k_0 a(n_1^2 - n_2^2)$, with k_0 the free space wave number and n_1 and n_2 the refractive indices of the core and cladding, respectively.

When the laser field reaches plane 1 which is at the nearest point of the surface of the fiber lens, it will pass through the hemispherical lens and be transformed, laser field on the plane 2 can be given by^[10]

$$\psi_v = \exp\left[-\left(\frac{x^2}{w_{2x}^2} + \frac{y^2}{w_{2y}^2}\right)\right] \exp\left[-jk_2\left(\frac{x^2}{2R_{2x}} + \frac{y^2}{2R_{2y}}\right)\right] \tag{4}$$

where k_2 is the wave number in the lens and w_{2i} and R_{2i} are spot size and radius of curvature in the lens transformed laser field, respectively. w_{2i} and R_{2i} can be found in terms of w_{1i} and R_{1i} through ABCD matrix relations^[12]. After simple manipulation, we get

$$w_{2i}^2 = \frac{(A + B/R_{1i})^2 w_{1i}^2 + \lambda_0^2 B^2 / \pi^2 w_{1i}^2}{n_2 [(A + B/R_{1i})D - (C + D/R_{1i})B]} \tag{5}$$

$$R_{2i} = \frac{(A + B/R_{1i})^2 + \lambda_0^2 B^2 / \pi^2 w_{1i}^4}{(A + B/R_{1i})(C + D/R_{1i}) + \lambda_0^2 BD / \pi^2 w_{1i}^4} \tag{6}$$

Further, the LD to fiber coupling efficiency via a hemispherical lens on the tapered fiber tip is given by the well-known overlap integral^[13]

$$\eta = \frac{\left| \iint \psi_v \psi_t^* dx dy \right|^2}{\iint |\psi_v|^2 dx dy \iint |\psi_t|^2 dx dy} \tag{7}$$

In order to estimate the coupling efficiency of designed lens, we use following parameters, namely a LD of wavelength $1.5\mu\text{m}$ with $w_{1x0} = 0.5\mu\text{m}$, $w_{1y0} = 1.0\mu\text{m}$, $n_1 = 1.462$, $n_2 = 1.451$, and a single-mode fiber with a core diameter $10\mu\text{m}$. From above calculation, one can obtain the dependence of maximum coupling efficiency on the taper length, and the result for a fixed R of $20\mu\text{m}$ is shown in Fig. 2. The maximum coupling efficiency decreases with the increase of the taper length. The experiment results are got by using the structure showed in Fig. 1. By carefully adjusting the distance of x, y, z axis between fiber and LD, we get the results. We can see that the experiment results are less about 30%

than the calculated. This is due to the approximations mentioned above. But we also can see that the trends of these two curves are identical. So we can think that the calculated result is fully supported by the experimental data. We also can get from the figure that the maximum coupling efficiency decreases with the increase of taper length. In this sense, shorter taper length (great taper angle) is preferred. But great taper angle will cause the fiber core-guided mode to couple to other higher-order cladding-guided modes than the fundamental cladding-guided mode and result in energy loss through mode coupling among cladding-guided modes. A trade-off has to be made between this effect and the maximum coupling efficiency.

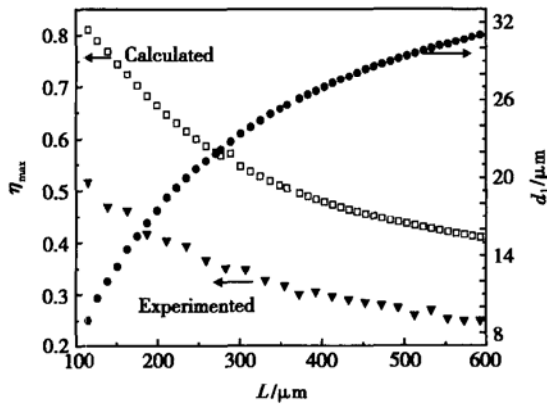


Fig. 2 Effect of taper length on the maximum coupling efficiency, as well as on the optimum working distance

2.2 Coupling efficiency with misalignment

We will discuss the case of existing lateral and angular misalignment ($d \neq 0$, $\theta \neq 0$). Equations (2) and (4) can not be used again. Rather, the respective field of fiber and laser source at the reference plane 2 must be given by

$$\psi_f = \exp\left[-\frac{(x-d_x)^2 + (y-d_y)^2}{w_f^2}\right] \quad (8)$$

$$\begin{aligned} \psi_v = & \exp\left[-\left(\frac{x^2}{w_{2x}^2} + \frac{y^2}{w_{2y}^2}\right)\right] \times \\ & \exp\left[-jk_2\left(\frac{x^2}{2R_{2x}} + \frac{y^2}{2R_{2y}}\right)\right] \exp[jky\theta_y + jkx\theta_x] \end{aligned} \quad (9)$$

where θ_x and d_x represent pitch (rotation around x -

axis) angular misalignments and lateral offsets along x -axis, respectively. While θ_y and d_y represent yaw (rotation around y -axis) angular misalignments and lateral offsets along y -axis, respectively. While θ is a very small angle. Using Eqs. (8) and (9) in Eq. (7), we get

$$\eta_{\theta_y} = \frac{\left| \int_{-\infty}^{\infty} \exp\left[-\left(\frac{y^2}{w_{2y}^2} + \frac{y^2}{w_f^2} + jk_2 \frac{y^2}{2R_{2y}} - jk_2 y \theta_y\right)\right] dy \right|^2}{\int_{-\infty}^{\infty} \exp\left(-\frac{2y^2}{w_{2y}^2}\right) dy \int_{-\infty}^{\infty} \exp\left(-\frac{2y^2}{w_f^2}\right) dy} \quad (10)$$

$$\eta_{d_y} = \frac{\left| \int_{-\infty}^{\infty} \exp\left[-\left(\frac{y^2}{w_{2y}^2} + \frac{(y-d_y)^2}{w_f^2} + jk_2 \frac{y^2}{2R_{2y}}\right)\right] dy \right|^2}{\int_{-\infty}^{\infty} \exp\left(-\frac{2y^2}{w_{2y}^2}\right) dy \int_{-\infty}^{\infty} \exp\left(-\frac{2y^2}{w_f^2}\right) dy} \quad (11)$$

Similarly, the expression for η_{θ_x} is obtained by replacing y in Eqs. (10) and (11) with x . The subscript i denotes d and θ . η_{θ_y} and η_{d_y} denote the coupling efficiency from y -axis direction with misalignment resulting from an offset d_y and yaw θ_y (tilt around y -axis), respectively.

The analytical results obtained from Eq. (11) allow us to evaluate the coupling efficiency as a function of lateral offsets as presented in Fig. 3. From Eq. (10) the pitch and yaw angular misalignment dependence of coupling efficiency is presented

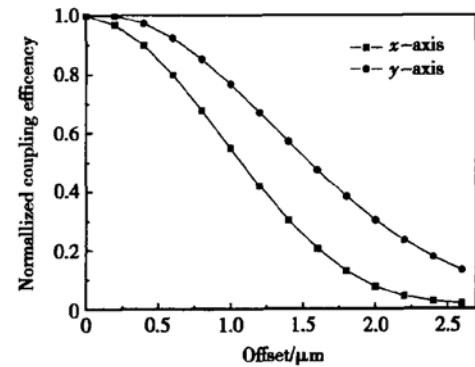


Fig. 3 Coupling efficiency versus x -, y -axis offsets

in Figs. 4 and 5, respectively. In Fig. 3, we think the taper length is $122\mu\text{m}$, the radius of hemispherical lens is $20\mu\text{m}$, and the working distance (d_1) is $10\mu\text{m}$. We can get from Fig. 3 that the normalized coupling efficiency decreases with the increasing of lateral offset. The coupling efficiency is a little

more sensitive to the y -axis offset than to x -axis offset. This is due to the waist spot size of LD in the y -axis (parallel to the LD junction) is 1.5 times larger than the x -axis' (perpendicular to the LD junction). In Figs. 4 and 5, the dependence of coupling efficiency on pitch and yaw angle is presented, according to three different taper angles. Comparing Figs. 4 and 5, it is evident that the pitch and yaw misalignment almost have same effect on the coupling efficiency. We can also observed from these two figures that the taper angle almost has no effect on the coupling efficiency in the presence of pitch misalignment, while has little effect on the coupling efficiency in the presence of yaw misalignment.

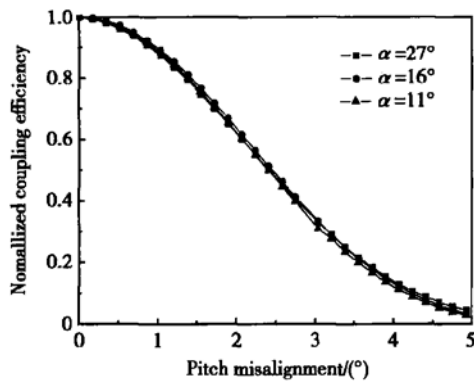


Fig. 4 Coupling efficiency versus pitch angle misalignment according to three different taper angle, namely taper lengths

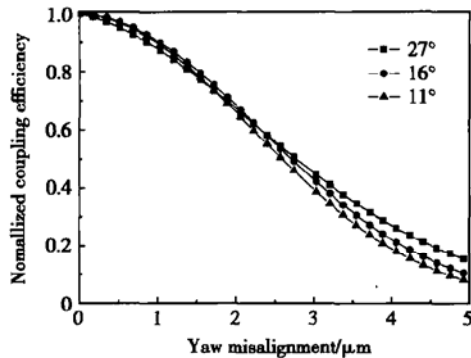


Fig. 5 Coupling efficiency versus yaw angle misalignment, according to three different taper angle, namely taper lengths

3 Conclusion

We have designed a tapered lensed SMF through theoretically investigating the effective coupling. Results show that in designing process, we have to think about the effect of these parameters on the coupling efficiency, including taper length, offset (transversal misalignment and angular mismatch). The coupling efficiency decreases with the increase of taper length and offset. The y -axis offset has sensitive effect on coupling efficiency than x -axis'. While the angular misalignment almost has same effect on coupling efficiency, and this result is almost not affected by the fiber taper angular, namely taper lengths.

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用于半导体激光器到单模光纤耦合的圆锥端微透镜设计

马 艳 谢福增

(中国科学院半导体研究所, 北京 100083)

摘要: 介绍了一种用于半导体激光器-单模光纤耦合的圆锥端半球透镜的耦合效率的理论计算. 失配不存在时, 耦合效率随着锥长的增加而减小. 失配存在时耦合效率随轴向和角向失配的增大而减小.

关键词: 高比特率通讯; 光纤耦合; 圆锥端透镜; 偏移

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