Optica Applicata, Vol. XXXIV, No. 2, 2004

Increasing semiconductor laser-optical fiber coupling efficiency by introducing microlens

M.S. OZYAZICI

University of Gaziantep, Department of Electrical and Electronics Engineering,
27310 Gaziantep, Turkey, e-mail: sadi@gantep.edu.tr

The efficiency of coupling between semiconductor lasers and single-mode optical fibers can be greatly increased by a microlens of an appropriate focal length being fabricated at the end of the fiber. The reason for this is that the lens can effectively improve the mode matching of the laser and fiber fields. Theoretical work has been carried out to predict this improvement of coupling efficiency as a function of the focal length and spot size associated with the laser and fiber. A simple method was then used to fabricate the microlenses whose focal lengths required a radius of curvature ranging from about 10 μm to 15 μm for maximum coupling. The method comprised in tapering of the fiber to the required radius using a grinder and then with an electric arc and heating the end which next forms into a hemisphere due to surface tension forces. Another way is to dip the tapered end into molten optical glass picking up a droplet of glass.

Keywords: semiconductor laser, optical fiber, coupling efficiency, microlens.

1. Introduction

Much attention is being given to the low-loss single mode fiber in the field of optical communication because of its very high bandwidth, making it a suitably long haul medium for large-capacity transmission systems [1].

In order to utilize fully this capability, an efficient power coupling between semiconductor laser and a single-mode fiber is necessary. A simple butt-joint method gives poor coupling efficiency, typically of the order of 10% because of mismatch of the laser and fiber fields. The main cause of mismatch is astigmatic and diverging nature of the beam emerging from the laser facet. To remove this mismatch and to reduce the coupling loss, a lens of an appropriate focal length is introduced to the end of the fiber which collimates the beam into the core. Many techniques have been developed to fabricate such microlenses [2]–[5].

Taking this into account, the theory used for determining butt jointing coupling efficiency and its extension to predict improved coupling efficiencies using lensed fibers is presented. This gives a design method for determining lens parameters for the optimum case when one deals with circular or an elliptical beam. A new fabrication method for microlenses is then reported.

A simple grinder is used to taper the fibers down to the radius required, which allows us to fabricate lenses of the appropriate focal length. The method of grinding keeps the fiber cores and the outer ground circumference quite concentric. That then is a simple matter to melt or dip the end in optical glass to form a hemisphere at the end of the taper which acts as a lens.

Coupling efficiencies of over 40% have been achieved as compared with only 10% for plane ended fibers.

Apart from fully utilizing the long haul capability of the single-mode fiber, high coupling efficiency could also make splice loss requirements less stringent when forming a long route by splicing a number of fibers together.

2. Theory

2.1. Gaussian fields

The mode field in a laser, whose power is to be coupled to a fiber that allows a single -mode propagation only, is approximated as a Gaussian [6], given by

$$E_{oL}(x, y, z) = A_L \exp\left(-\frac{x^2}{W_{ox}^2} - \frac{y^2}{W_{oy}^2}\right) \exp(-jkz). \tag{1}$$

This describes an elliptical beam of amplitude spot size W_{ox} in the x direction and W_{oy} in the y direction.

When solving Maxwell's equation for a dielectric waveguide of a circular cross section, the single-mode field propagating in the guide is made up of a Bessell function inside the core and a Hankel function in the cladding (a function that describes a decaying field away from the core) and for the sake of a good approximation this can be expressed as a Gaussian [7] given by

$$E_{oF}(x, y, z) = \frac{(2/\pi)^{1/2}}{W_f} \exp\left(-\frac{x^2 + y^2}{W_f^2}\right) \exp(-jkz). \tag{2}$$

The constant $(2/\pi)^{1/2}/W_f$ is a normalizing factor such that $\iint E_{oF} E_{oF}^* \mathrm{d}x\, \mathrm{d}y = 1$.

The beam from the laser diverges as diffraction takes place at the facet. The diffracted field at any point can be obtained based on the Fourier diffraction theory by taking the Fourier transform of $E_{oL}(x, y, z)$. This is expressed as

$$E_{LD}(x, y, z)$$

$$= A_L \left[\frac{W_{ox} W_{oy}}{W_x(z) W_y(z)} \right]^{1/2} \exp\left\{ \left[-\frac{x^2}{W_x(z)^2} - \frac{y^2}{W_y(z)^2} \right] - \left[\frac{jkx^2}{2R_x(z)} + \frac{jky^2}{2R_y(z)} \right] \right\} \exp(-jkz) \tag{3}$$

where $R_x(z)$ and $R_y(z)$ are the radii of curvature of the wavefronts of the diffracted beam with respect to the x and y directions as a function of z (separation from the laser). These are given as

$$R_{x,y}(z) = z \left[1 + \left(\frac{\pi W_{ox,oy}^2}{\lambda z} \right)^2 \right], \tag{4}$$

and $W_x(z), W_y(z)$ describes the spread of Gaussian waists

$$W_{x,y}(z) = W_{ox} \left[1 + \left(\frac{\lambda z}{\pi W_{ox,oy}^2} \right)^2 \right]^{1/2}. \tag{5}$$

2.2. Coupling formula

If butt coupling is used, E_{LD} is the input field to the fiber end and the amount of power from the field that is coupled as a guided single mode in the fiber can be found by expressing this input field as a Fourier sum of all the modes in the fiber

$$E_{LD} = \sum_n C_n E_{nF}. \tag{6}$$

In a single-mode fiber, only one mode can be propagated so the rest of the sum represents radiation modes. Using the orthogonality condition one can find the coefficient C_o which corresponds to the guided mode in the fiber where coupling efficiency is given by

$$C_e = |C_o|^2. \tag{7}$$

The use of

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} E_{mF} E_{nF}^* \mathrm{d}x \, \mathrm{d}y = \delta_{mn}, \text{ while } \delta_{mn} = 0 \text{ for } m \neq n, \ \delta_{mn} \neq 0 \text{ for } m = n,$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_{LD}\,E_{oF}^{*}\,\mathrm{d}x\,\mathrm{d}y = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\left(\sum_{n} C_n\,E_{nF}\right)E_{oF}^{*}\,\mathrm{d}x\,\mathrm{d}y$$
$$= \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} C_o E_{oF}\,E_{oF}^{*}\,\mathrm{d}x\,\mathrm{d}y, \tag{8}$$

where E_{oF}^{*} is the complex conjugate of E_{oF}, implies

$$C_e = |C_o|^2 = \left|\frac{\iint E_{LD}\,E_{oF}^{*}\,\mathrm{d}x\,\mathrm{d}y}{\iint E_{oF}\,E_{oF}^{*}\,\mathrm{d}x\,\mathrm{d}y}\right|^2. \tag{9}$$

Now $\iint E_{oF}\,E_{oF}^{*}\,\mathrm{d}x\,\mathrm{d}y$ is proportional to the power in the mode, which has been normalized. Therefore

$$C_e = \left|\iint E_{LD}\,E_{oF}^{*}\,\mathrm{d}x\,\mathrm{d}y\right|^2. \tag{10}$$

If the power in the laser mode has not been normalized, then

$$C_e = \frac{\left|\iint E_{LD}\,E_{oF}^{*}\,\mathrm{d}x\,\mathrm{d}y\right|^2}{\iint E_{oL}\,E_{oL}^{*}\,\mathrm{d}x\,\mathrm{d}y}. \tag{11}$$

2.3. Coupling efficiency

Inserting Eqs. (1), (2) and (3) into the above coupling formula gives

$$C_e = \frac{4}{W_x(z)\,W_y(z)\,W_f^2}\left[\left(\frac{1}{W_x(z)^2}+\frac{1}{W_f^2}\right)^2+\frac{k^2}{4R_x(z)}\right]^{-1/2}$$
$$\times\left[\left(\frac{1}{W_y(z)^2}+\frac{1}{W_f^2}\right)^2+\frac{k^2}{4R_y(z)^2}\right]^{-1/2}. \tag{12}$$

This is the coupling efficiency between Gaussian elliptical beam and a monomode fiber of spot size W_f. For a circular beam $W_{ox} = W_{oy}$ and $R_x(z) = R_y(z)$ it follows that

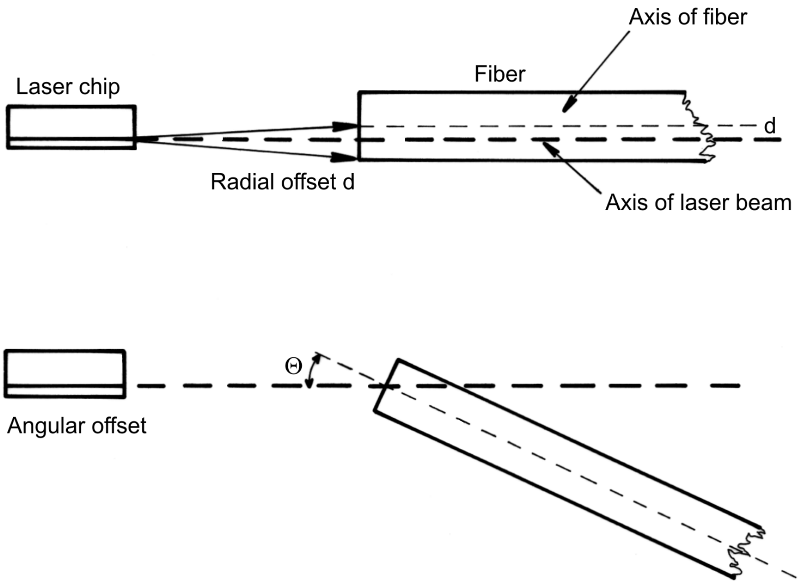

Fig. 1. Possible offsets that can occur between the axis of a laser beam and the axis of an optical fiber.

$$C_c = \frac{4W(z)^2 W_f^2}{\left[W_f^2 + W(z)^2\right]^2 + \dfrac{k^2 W_f^2 W(z)^2}{4R(z)^2}}. \tag{13}$$

3. Offset coupling efficiency

The parameter C_e derived above was in terms of longitudinal offset. We wish to know the variation of coupling efficiency as a function of radial and angular offset as shown in Fig. 1.

3.1. Radial offset

To determine the coupling efficiency for this situation, we express the mode in the fiber as an off-axis Gaussian given by

$$E_{oF}(x, y, z) = \frac{(2/\pi)^{1/2}}{W} \exp\left\{-\frac{(x+x')^2 + (y+y')^2}{W_f^2}\right\} \exp(-jkz) \tag{14}$$

where x' and y' are the offsets with respect to x and y directions. Inserting this into the coupling formula and using the general integral

$$\int_{-\infty}^{\infty} \exp\left\{-(at^2 + 2bt + c)\right\} \mathrm{d}t \cong \left(\frac{\pi}{a}\right)^{1/2} \exp\left(\frac{b^2 - ac}{a}\right), \tag{15}$$

for an elliptical beam we obtain

$$C_{re} = C_e C_x C_y$$

where C_e is given in Eq. (12) and

$$C_x = \exp\left\{-2x'^2 \frac{\left[1/W_f^2 W_x(z)^2\right]\left[1/W_x(z)^2 + 1/W_f^2\right] + k^2/4R_x(z)^2 W_f^2}{\left[1/W_x(z)^2 + 1/W_f^2\right]^2 + k^2/4R_x(z)^2}\right\} \tag{16}$$

and similarly with C_y using y', $W_y(z)$, $R_y(z)$, instead. For a circular beam

$$W_{ox} = W_{oy}\, R_x(z) = R_y(z)$$

and since $x'^2 + y'^2 = d^2$ (see Fig. 2), we arrive at

$$C_{rc} = C_c \exp\left\{-2d^2 \frac{\left[1/W_f^2 W(z)^2\right]\left[1/W(z)^2 + 1/W_f^2\right] + k^2/4R(z)^2 W_f^2}{\left[1/W(z)^2 + 1/W_f^2\right]^2 + k^2/4R(z)^2}\right\} \tag{17}$$

where C_c is given in Eq. (13).

Equation (17) is similar to Marcuse's fiber-to-fiber radial offset Eq. (3) that determines fiber spot size except that in Marcuse's equation $R(z) = \infty$ and $W(z) \neq f(z)$ and it reduces to

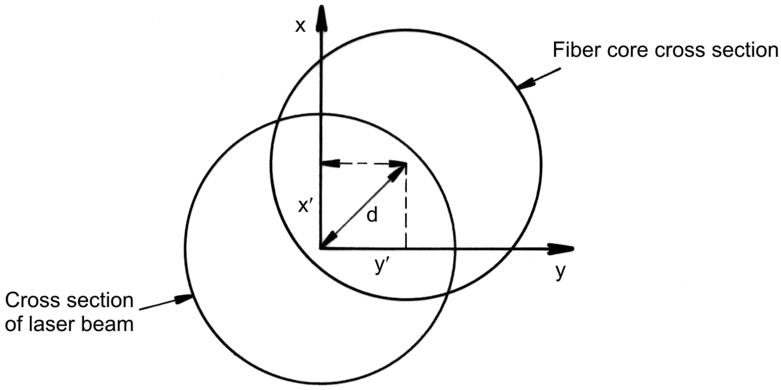

Fig. 2. Offset (x', y') between the axis of a laser beam and the axis of the fiber core.

$$C_{cfib} = \frac{4W_1^2W_2^2}{\left(W_1^2 + W_2^2\right)^2}\exp\left(-\frac{2d^2}{W_1^2 + W_2^2}\right)$$

where W_1 and W_2 are the spot sizes of the fibers.

3.2. Angular offset

Figure 3 shows the fiber having an angular offset of Θ. In the plane of the fiber end (x_1, y_1), the single mode propagates in the direction s given by:

$$E_{oF}(x_1, y_1, s) = \frac{(2\pi)^{1/2}}{W_f}\exp\left(-\frac{x_1^2 + y_1^2}{W_f^2}\right)\exp(-jks). \tag{18}$$

This is expressed in terms of the coordinates in the xy plane of the laser facet such that

$$x_1 = x, \quad y_1 = y\cos\Theta + z\sin\Theta, \qquad s = y\sin\Theta + z\cos\Theta.$$

If Θ is small ($\sin\Theta$ X Θ, $\cos\Theta$ X1), then

$$E_{oF}(x, y, z) = \frac{(2/\pi)^{1/2}}{W_f}\exp\left\{-\left(\frac{x^2}{W_f^2} + \frac{y^2}{W_f^2} + jky\Theta\right)\right\}\exp(-jkz).$$

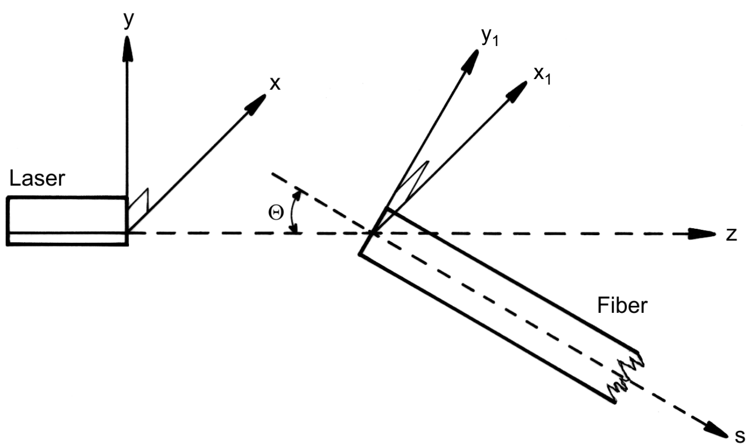

Fig. 3. Angular offset between fiber and laser beam. The facet of the fiber is parallel to the (x_1, y_1) plane and the single-mode field in the fiber is in terms of these coordinates. To calculate angular offset coupling efficiency this single mode field is expressed in terms of the x', y' coordinates using transformations that give x_1, y_1 in terms of x, y.

Inserting this into the coupling formula and using the general integral we obtain

$$\int_{-\infty}^{\infty} \exp(\alpha y \pm j\beta y)\,\mathrm{d}y = \left(\frac{\pi}{\alpha}\right)^{1/2} \exp\left(\frac{-\beta^2}{4\alpha}\right),$$

$$C_\Theta = C_e \exp\left\{-2\,\frac{\pi^2 n^2 \Theta^2\left[1/W_y(z)^2 + 1/W_f^2\right]}{\lambda^2\left[1/W_y(z)^2 + k^2/4R_y(z)^2\right]}\right\} \tag{19}$$

where C_e is defined by Eq. (12), λ is the free space wavelength and n is the refractive index of the core. The above is due to an offset with respect to the y direction if an elliptical beam is incident on the fiber. With offset, in respect of the x direction, we must use $W_x(z)$, $R_x(z)$ in the exponential. For a circular beam, C_e becomes C_c in Eq. (13) since $W_y(z) = W_x(z)$, $R_x(z) = R_y(z)$.

4. Mode matching improvement between laser and a single-mode fiber by using microlens

The above coupling efficiencies were derived for butt jointing which is quite low (10%) when typical values are put in Eq. (13), as shown in Fig. 4. This has been confirmed by experiment.

To get maximum coupling the laser field has to be perfectly matched with the field allowing propagation in the fiber. In other words, the incident field has to have the same distribution and in turn the same spot size as that of the fiber. The distance of

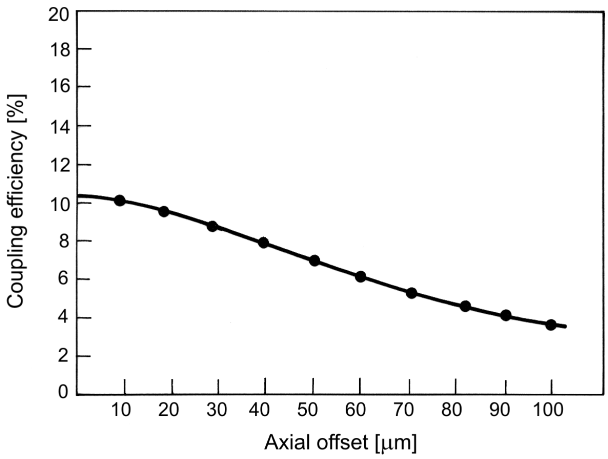

Fig. 4. Theoretical plot of coupling efficiency C_o against axial offset.

the fiber from the laser can be adjusted in such a way that $W(z) = W_f$ or the spot size of the beam matches that of the fiber.

Using Eq. (13) for the efficiency of coupling between a circular Gaussian laser beam and a single-mode fiber for $W(z) = W_f$, we obtain

$$C_c = \frac{1}{1 + k^2/16R(z)^2}. \tag{20}$$

This equation shows that the only factor responsible for coupling loss is the finite curvature of the beam wavefront, or the divergence of the beam. For perfect coupling it is required that $R(z) \to \infty$, *i.e.*, to collimate the beam into the core. This can be done using a microlens of an appropriate focal length.

The focal length of a lens of thickness t, using the paraxial ray approximation, is given by

$$\frac{1}{f} = \frac{n_L - 1}{r_L} - \left(n_L - \frac{n_o}{r_R} + \frac{t}{r_R}\right)(n_L - 1)\left(n_L - \frac{n_o}{n_L}\right). \tag{21}$$

In our case, $r_R = \infty$ and this implies that

$$f = \frac{r_L}{n_L} - 1. \tag{22}$$

If the lens is also assumed to behave as an ideal phase transformer, then the coefficient of transmission through the lens is given by

$$T(x, y) = \exp\left\{-\frac{jk(x^2 + y^2)}{2f}\right\}. \tag{23}$$

This is multiplied by the laser field E_{LD} and the new modified field (TE_{LD}) is insert into the coupling formula to determine the following new coupling efficiency:

$$C_{ef} = \frac{4}{W_x(z)W_y(z)W_f^2}\left[\left(\frac{1}{W_x(z)}\right)^2 + \left(\frac{k}{2R_x(z)} - \frac{k}{2f_x}\right)^2\right]^{-1/2}$$
$$\times \left[\left(\frac{1}{W_y(z)^2} + \frac{1}{W_f^2}\right)^2 + \left(\frac{k}{2R_y(z)} - \frac{k}{2f_y}\right)^2\right]^{-1/2} \tag{24}$$

where C_{ef} is a general expression for coupling an elliptical beam to a fiber tipped with a elliptical lens of the focal lengths f_x, and f_y with respect to the x and y directions.

For a circular beam and hemispherical lens $W_x(z) = W_y(z)$, $R_x(z) = R_y(z)$, $f_x = f_y$ and

$$C_{cf} = \frac{4}{W_f^2 W(z)^2}\left[\frac{1}{W_f^2} + \frac{1}{W(z)^2} + \left(\frac{k}{2R(z)} - \frac{k}{2f}\right)^2\right]^{-1}. \tag{25}$$

The expressions for:

– radial offset

$$C_{ref} = C_{ef} C_{xf} C_{yf},$$

$$C_{xf} = \exp\left\{-2x'^2 \frac{\dfrac{1}{W_f^2 W_x(z)^2} - \left[\dfrac{1}{W_x(z)^2} + \dfrac{1}{W_f^2}\right] + \dfrac{k^2}{4}\left[\dfrac{1}{R_x(z)} - \dfrac{1}{f_x}\right]^2}{\left[\dfrac{1}{W_x(z)^2} + \dfrac{1}{W_f^2}\right]^2 + \dfrac{k^2}{4}\left[\dfrac{1}{R_x(z)} - \dfrac{1}{f_x}\right]^2}\right\} \tag{26}$$

similarly with C_{yf} but using y', $W_y(z)$, $R_y(z)$, f_y instead. For a circular beam and hemispherical lens

$$C_{rcf} = C_{cf} \exp\left\{-2d^2 \frac{\dfrac{1/W(z)^2 + 1/W_f^2}{W_f^2 W(z)^2} + \dfrac{k^2}{4}\left[\dfrac{1}{R(z)} - \dfrac{1}{f}\right]^2}{\left[\dfrac{1}{W(z)^2} + \dfrac{1}{W_f^2}\right]^2 + \dfrac{k^2}{4}\left[\dfrac{1}{R(z)} - \dfrac{1}{f}\right]^2}\right\}; \tag{27}$$

– angular offset

$$C_{of} = C_{cf} \exp\left\{-2 \frac{\left[\pi^2 n^2 \Theta^2 (1/W_y(z)^2 + 1/W_f^2)\right]/\lambda^2}{\dfrac{1}{W_y(z)^2} + \dfrac{1}{W_f^2} + \dfrac{k^2}{4}\left[\dfrac{1}{R_y(z)} - \dfrac{1}{f_y}\right]^2}\right\}. \tag{28}$$

This angular offset is with respect to the y direction. Replace $W_y(z)$, $R_y(z)$, f_y with $W_x(z)$, $R_x(z)$, f_x for offset with respect to x direction.

5. Design of lens for maximum coupling efficiency

Taking the example of a circular beam and hemispherical lens and making use of Eq. (25) we can conclude that for a given fiber spot size W_f the only parameters that can be varied to improve coupling efficiency are $W(z)$, or the beam spot size which can be varied by changing the distance between fiber and laser, and f, or the focal length of the lens.

It has been mentioned that for a perfect coupling we need to collimate the beam into the core at $W(z) = W_f$ (see Eq. (20)). This can also be seen in the differential of Eq. (25) with respect to z and f. For maximum coupling:

$$\frac{\partial C_{cf}}{\partial f} = 0, \tag{i}$$

$$\frac{\partial C_{cf}}{\partial z} = 0. \tag{ii}$$

For (i) to be satisfied, the condition is $f = R(z)$ or the focal length of the lens must equal the radius of curvature of the wavefront of the beam. If condition of $f = R(z)$ is inserted into equation (ii) then $W(z) = W_f$ for (ii) is satisfied. The conditions for maximum coupling efficiency are therefore $W(z) = W_f$ and $f = R(z)$. So to design the lens for maximum coupling, we determine the value of z for which $W(z) = W_f$ and then we insert this value into the expression for $R(z)$ to determine f, where $R(z)$ is

$$f = R(z) = z\left[\left(\frac{\pi W_o^2}{\lambda z}\right)^2 + 1\right]$$

where W_o is the beam spot size of the laser at the facet.

5.1. Hemiellipsoidal lenses

If the beam spot sizes, W_{ox} and W_{oy}, parallel and perpendicular to the laser junction plane, differ, then it is better to provide two different lens radii in the two directions to improve the coupling efficiency or, in other words, to collimate the elliptical beam emerging from the laser. Thus one of the conditions for maximum coupling is similar to the case for a circular beam and hemispherical lens, *i.e.*, $f_x = R_x(z)$, $f_y = R_y(z)$, remembering that in the circular beam case $f_x = f_y$ and $R_x(z) = R_y(z)$.

The distance z between a lensed fiber and a laser which will give the best $W_x(z)$, $W_y(z)$ for maximum coupling (which will also determine f_x, f_y) can be found when $\partial C_{ef}/\partial z = 0$. This involves very tedious algebra, and an alternative way is to solve Eq. (24) using a computer with the conditions $f_x = R_x(z)$, $f_y = R_y(z)$. This reduces Eq. (24) to

$$C_{ef} = \frac{4}{W_x(z)/W_f + W_f/W_x(z)},$$

now

$$W_y(z) = W_{oy}\left[1 + \left(\frac{z\lambda}{\pi W_{oy}^2}\right)^2\right]^{1/2},$$

$$W_x(z) = W_{ox}\left[1 + \left(\frac{z\lambda}{\pi W_{ox}^2}\right)^2\right]^{1/2}$$

where W_{ox} and W_{oy} are the spot sizes of the laser parallel and perpendicular to the junction plane and simultaneously the constants of a given laser. By using an array of values of z in the computer, the optimum distance of the fiber from the laser is found for which C_{ef} is maximum.

For example, if $W_{ox} = 0.6$, $W_{oy} = 1.8$ and $W_f = 5.374$ (these are amplitude spot sizes associated with typical lasers and fibers), the conditions for maximum coupling for this optimum distance z are found as

$$W_x(z) = 1.413\,W_f,$$

$$W_y(z) = 0.577\,W_f,$$

where $z = 11$ μm.

Having obtained the value of z for maximum coupling, we can determine f_x and f_y based on the first condition for maximum coupling

$$f_x = R_x(z) = z\left[\left(\frac{\pi W_{ox}^2}{\lambda z}\right)^2 + 1\right] \sim 11\ \mu\text{m},$$

$$f_y = R_y(z) = z\left[\left(\frac{\pi W_{oy}^2}{\lambda z}\right)^2 + 1\right] \sim 16.5\ \mu\text{m}.$$

These values of f_x, f_y and z will theoretically give the maximum possible coupling efficiency which, in this example, is about 81%, assuming that the lens behaves as an ideal phase transformer.

5.2. Theoretical curves of coupling efficiency as a function of axial and radial offsets for various focal lengths

The far-field radiation patterns of a semiconductor laser are usually given in terms of angular displacement and one can use Eq. (5) to obtain the spot size of the laser. Equation (5) describes the amplitude waist spread of the Gaussian beam as a function of distance (or the amplitude beam spot size)

$$W(z) = \left[1 + \left(\frac{z\lambda}{\pi W_o^2}\right)^2\right]^{1/2} .$$

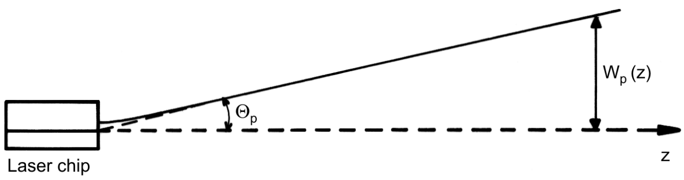

Fig. 5. Gaussian waist $W_p(z)$ diverging with the distance z from the facet of a semiconductor laser due to diffraction.

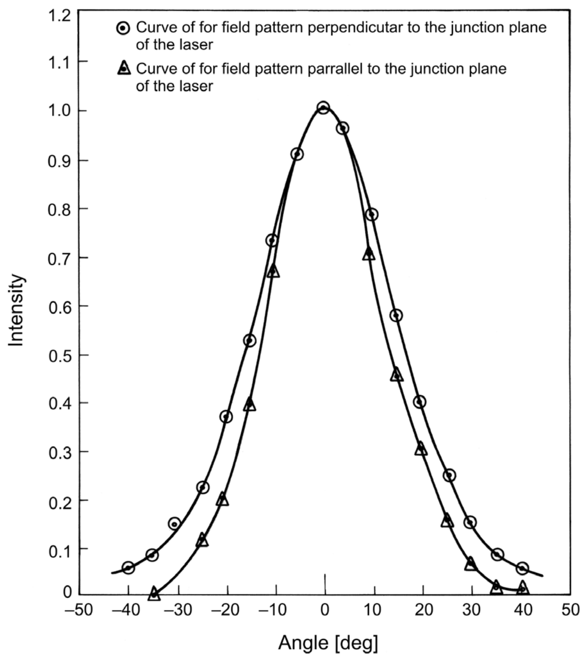

Fig. 6. Normalized far-field patterns of a Hitachi semiconductor laser.

For far-field condition when z is large

$$\frac{z\lambda}{\pi W_o^2}\mathrm{W1}$$

and it follows that

$$W(z) = \frac{z\lambda}{\pi W_o^2} \tag{29}$$

where W_o is the spot size required.

In Figure 5, $W_p(z)$ is the power spot size at a distance z from the laser at an angle Θ_p, where Θ_p is the angular power spot size of the laser or the angle at which the power drops to e^{-1} of its value. Therefore, $W_p(z) = z\tan\Theta_p$.

As $W(z)$ in Eq. (29) is the amplitude spot size, then

$$W(z) = \sqrt{2}W_p(z) = z\sqrt{2}\tan\Theta_p.$$

It follows that amplitude spot size of the laser is

$$W_o = \frac{\lambda}{\sqrt{2}\pi\tan\Theta_p}. \tag{30}$$

Using the Hitachi radiation patterns in Fig. 6 one can obtain W_{ox} and W_{oy} using Eq. (30), where $W_{ox} = 0.8$, $W_{oy} = 1$. Using computer, the plots representing coupling efficiency

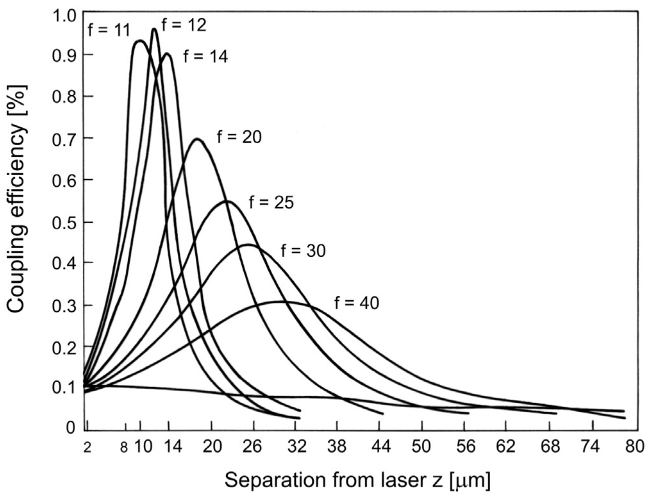

Fig. 7. Theoretical plot of coupling efficiency against axial offset.

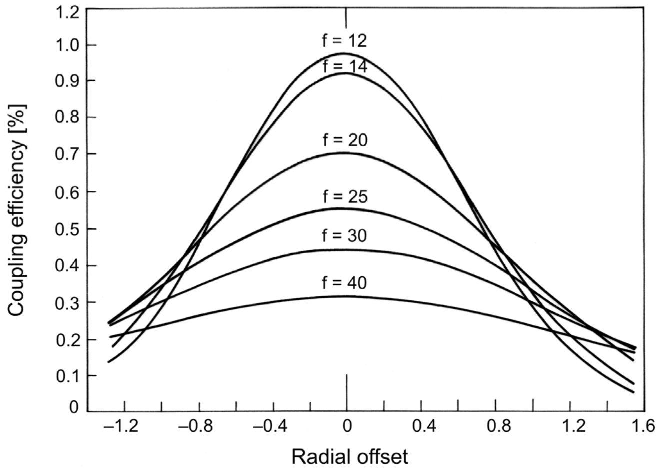

Fig. 8. Theoretical plot of coupling efficiency against radial offset.

for a function of *z* were obtained for lensed fibers of various focal lengths (Fig. 7). Equation (24) was used for calculating the coupling efficiency but with $f_x = f_y$ or for a hemispherical lens.

Theory shows that it is still possible to obtain 97% coupling efficiency with a hemispherical lens of about 12 μm focal length because the beam from the laser is close to a circular beam. The curves show how the coupling efficiency varies with focal length, displaying that its variation with axial offset becomes more critical as the optimum case is approached. The bottom curve is the case for $f = \infty$ or a plane ended fiber showing that only 10% coupling is possible and the variation of coupling efficiency with axial offset is considerably less critical. Figure 8 shows the curves of coupling efficiency variation with radial offset.

6. Fabrication of the microlenses

We have already shown that for good coupling efficiency we require a microlens of focal length in the range of 10–15 μm.

One way of achieving these focii is to grind down the fiber to a certain radius, or to taper it using a grinder and then to round off the pointed end. A simple grinder has been made which successfully gives good tapered ends down to 4 μm in radius. It consists of an aluminium flywheel which is turned at a very fast speed (4000 r.p.m.) by an electric motor upon which grinding papers of various grit sizes can be placed.

The fiber is lowered at an angle on the grinding paper and flexed a little to provide a pressing force on the grit. A silicon carbide paper with a grit size of 3 μm is used. The fiber is supported by a capillary tube which is fixed through a pulley connected to another identical pulley by a fan belt rotated by an electric motor at about 20 r.p.m.

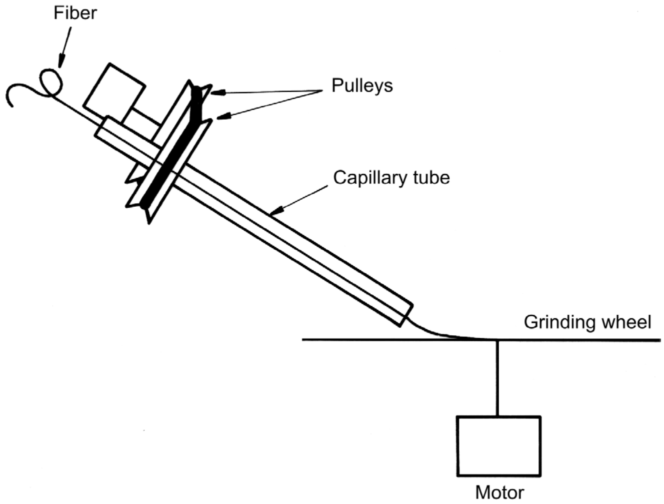

Fig. 9. Grinder for tapering fibers prior to lensing.

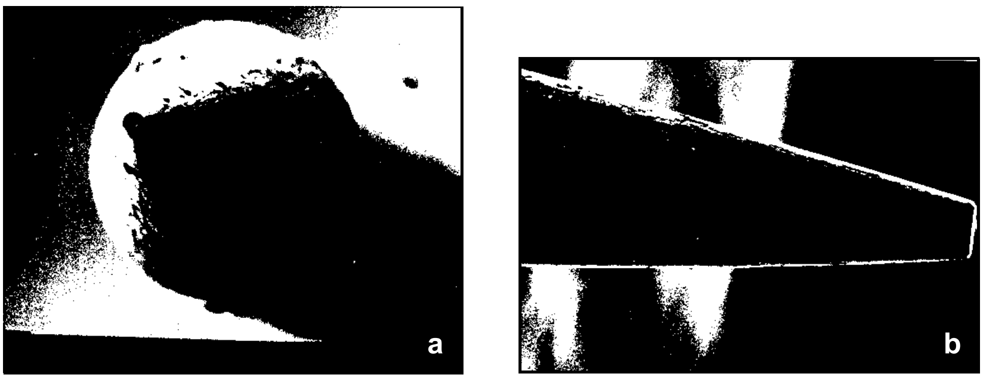

Fig. 10. Micrographs of tapered fibers; **a** – 4 µm, **b** – 13 µm.

Figure 9 shows a diagram of the grinder and the electron microscope pictures, while Fig. 10**a** and 10**b** show fibers ground up to about 4 µm and 13 µm in radius in about 3 min.

After the fiber has been tapered down to a certain radius r_L, an electric arc can be used to melt the end, after which, surface tension forces pull the end into a hemisphere which can act as a lens, having a radius of curvature r_L and therefore a focal length given by

$$f = \frac{r_L}{n - 1}$$

where n is the refractive index of the fiber.

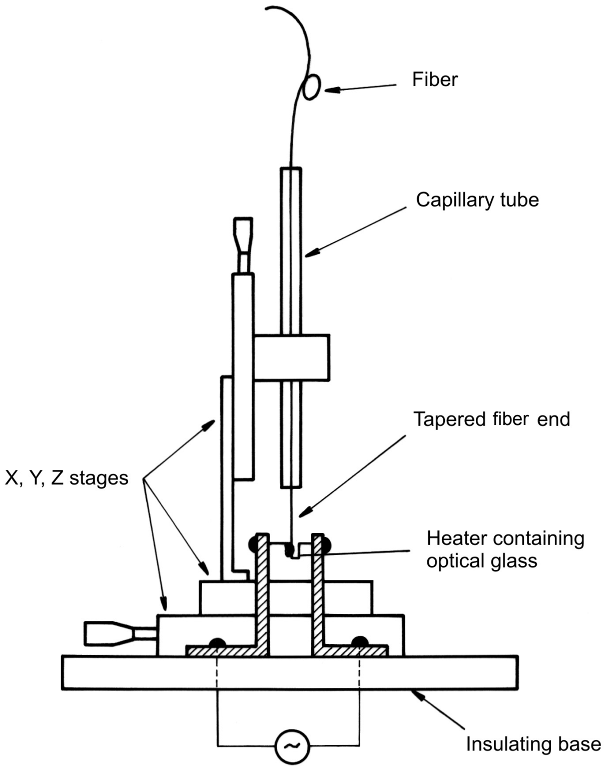

Fig. 11. Apparatus used for fabricating lenses at the ends of tapered fiber for dipping in molten optical glass.

Another technique is to dip the tapered fiber in molten optical glass which softens at a much lower temperature than the fiber and then pull it out, forming a hemispherical lens at the tip of the taper, see Fig. 11. This second technique provides two degrees of freedom in achieving the desired focal lengths since the refractive index of the glass used to form the lens can also be varied.

By using these two techniques we can fabricate microlenses of radius 3 μm in focal length.

7. Results and conclusions

The fabricated lens was measured to have a curvature similar to that required for maximum coupling efficiency. It had a focal length of about 15 μm which according to theory should give about 90% coupling efficiency assuming the lens acts as an ideal transformer. The maximum coupling efficiency achieved with that lens is about 43% at about 13 μm away from the laser.

These results were repeated a number of times with good consistency, with other fibers tipped with microlenses, fabricated by both techniques, the electric arc and the dipping method. The microlenses that were fabricated using the dipping method gave a lower coupling efficiency. This could be attributed to the high refractive index $n = 1.953$, which would cause high reflection losses at the interface of the lens with the fiber core. When using microlenses on the ends of tapered fibers, the results show an increase in coupling efficiency of about four times compared to plane ended fibers. The theory, which is based on the Gaussian model, predicts coupling efficiencies very close to the experimental ones for plane-ended fibres. It also allows predicting the correct lens parameters for optimum coupling efficiency when using lensed fibers, although the experimental curves representing coupling efficiency are not very close to the theoretical ones. However, both curves, theoretical and experimental, peak at about the same point when looking at axial offset and are similar in shape.

The difference between predicted values and experimental ones is most likely attributed to two causes:

– the assumption that the lens acts as an ideal phase transformer (thin lens); in practice, this is not the case as we are clearly producing a thick lens;

– the fabrication methods might not produce the desired lens parameters due to extraneous events, such as impure glass or temperature causing lens deformation.

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Received October 10, 2003