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Effective coupling from semiconductor lasers to single mode fibers

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The coupling efficiency can be improved when the output field from the laser is matched to the output field of the fiber, which can be usually achieved using a lens positioned between the laser and the fiber. A simple and popular method is to employ a hemispherical lens formed at the end of a tapered optical fiber. To obtain a tapered end with hemispherical lens a simple process of pulling this fiber in the electrical arc is used. In the experiments we measured coupling efficiency between semiconductor lasers of different divergence angles of the laser beam and tapered fibers. The coupling efficiency up to 35% is usually possible to obtain, when for flat end fiber it is only 10%. Influences of reflected light, such as threshold current change, power fluctuation, and noise generation, are much smaller for tapered than for flat-end fibers.

1. Introduction

One of the major difficulties with using semiconductor lasers within optical fiber communication systems concerns the problem associated with the efficient coupling of light between the laser and the optical fiber (particularly single mode fiber with its small core diameter and low numerical aperture). Thus butt coupling efficiency from the laser to the fiber is often low at around 10%, even with good alignment and the use of the fiber with a well cleaved end. In this case, the optimum coupling efficiency is obtained by positioning the fiber end very close to the laser facet. Unfortunately, this technique allows back reflections from the fiber, which produce noise at the device output and can cause performance degradation in high speed systems.

The coupling efficiency can be improved when the output field from the laser is matched to the output field of the fiber. Such matching is usually achieved using a lens (or lens system) positioned between the laser and the fiber. If we employ a hemispherical lens formed at the end of a taper optical fiber, the number of piece-parts are therefore minimised and only one alignment step is required.

This coupling technique is attractive also because of the relative ease of fabrication, reasonable coupling efficiency and relatively reduced influence of the reflected light.

2. Theory

The tapering has significant effect on the optical field as it propagates along the taper. It is assumed that in the tapered region the cladding and the core radii decrease with the same ratio while the fiber is drawn. Initially the field is guided by, and substantially confined to the core. As the core diameter decreases the field spreads out, its spot size increases. Enlargement of the spot size radius of the fundamental Gaussian mode along the tapered section can be described by the following empirical equation [1]:

$$w_f = a(0.85+3.04\ V^{-3}+1.28\ V^{-9}) \tag{1}$$

where: $V = 2\pi/\lambda_0 a\sqrt{2n_c \Delta n}$, a is the radius of the fiber core and λ_0 is the vacuum wavelength, n_c is the refractive index of the fiber core, and Δn is the difference in refractive indices between the core and the cladding.

Eventually the point is reached when the field is no longer guided by the core but is effectively guided by the waveguide consisting of the cladding and surrounding medium. The cladding waveguide is highly multimoded and, if the taper rate is large, coupling to higher order modes will occur, resulting in power loss from the output of the taper. The condition for a taper to remain adiabatic, which means that taper angle is very small and changes very slowly along the fiber length, is [2]:

$$\left|\frac{da}{dz}\right| \ll \frac{a}{z_b},\quad z_b = \frac{2\pi}{\beta_1-\beta_2} \tag{2}$$

where β_1, β_2 are the propagation constants of the LP_{01} and LP_{02} cladding modes and z_b is the beat length. A taper satisfying this condition will suffer negligible loss through mode coupling.

When the propagating light passes through the lens on the tip of the taper, with the radius of curvature of R and refractive index n_l, a spot size radius w_f is transformed to another one w_1, according to the relation [3]

$$w_1 = w_f\left[1+\left(\frac{\pi(n_l-1)w_f^2}{\lambda_0 R}\right)^2\right]^{-1/2} \tag{3}$$

In the derivation the assumptions were made that the modal field profile of the fiber is well described by a Gaussian field [1] and the hemispherical lens acts as a thin lens, *i.e.*, the fiber core is present up to the apex of the lens. It can be approved that optimum coupling separation between the laser diode and the lens and the optimum lens radius R increase as the spot size radius at the taper end also increases. It can be theoretically shown that amount of light reflected from the fiber end towards the laser decreases more the larger the spot size radius at the taper tip.

In the situation of coupling from the laser to the lensed fiber we have to consider the opposite direction of light propagation. The diverging light emission from the laser is converted by the hemispherical fiber tip. A nearly parallel beam propagates in the tapered region of the fiber, while the width of the characteristic field in the tapered core region decreases as the core radius increases. Therefore, the converted laser beam radius matches the field radius of the fiber.

3. Fiber processing and coupling experiments

The tapered lensed fiber (see Fig. 1) is fabricated by drawing it in the arc discharge of a splicer. The hemispherical tip is produced by the surface tension of the molten cladding glass. Reproducibility of the radius of the end hemisphere is good if conditions, such as arc discharge voltage, drawing velocity, and separation between the electrodes are constant.

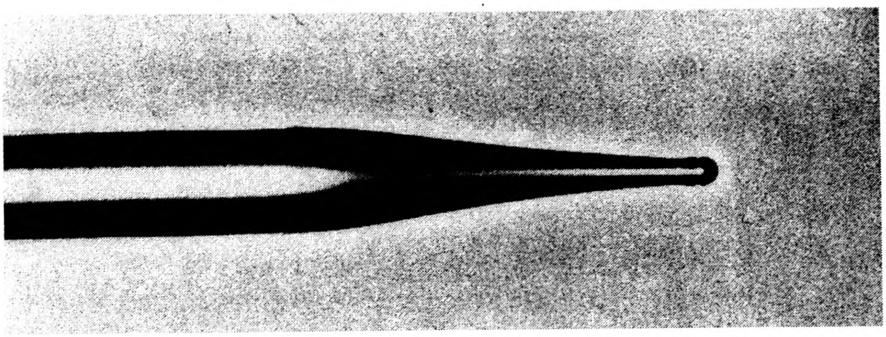

Fig. 1. Tip of the tapered lensed fiber

To evaluate the taper, and to find the symmetry of the created lens, spot size radius of the focus of this lens, the radiated far-field intensity distribution is measured while the laser output power is coupled into the fiber from the other end (see Fig. 2). Fiber length is around 1 m. The far-field angle Θ_{FWHM} (full width half maximum), if Gaussian-like in shape, is related to the spot size radius by the expression

$$\Theta_{FWHM} = (2\ln 2)^{-1/2}\tan^{-1}\frac{\lambda_0}{\pi w_1}. \tag{4}$$

The far field intensity distribution indicates that the output light from the fiber is in the propagation mode. From the shape of far field profile we can obtain information about the symmetry of the lenses [4]. The more symmetrical lens the better coupling efficiency is possible to obtain. Far field measurements were done also for lasers (see Fig. 3) to establish the divergence of the radiated beam and to compare their far field characteristics with those obtained for lensed fibers.

In the coupling experiments four semiconductor lasers of different divergence angles of the laser beam were used at temperature of 20 °C. In our experiments we measured 6 tapered fibres and one flat end fiber. A large area Ge photodiode was used to detect the laser output power, and coupling experiments were carried out by using precise manipulators with piezoelectric translators. Coupling efficiency was

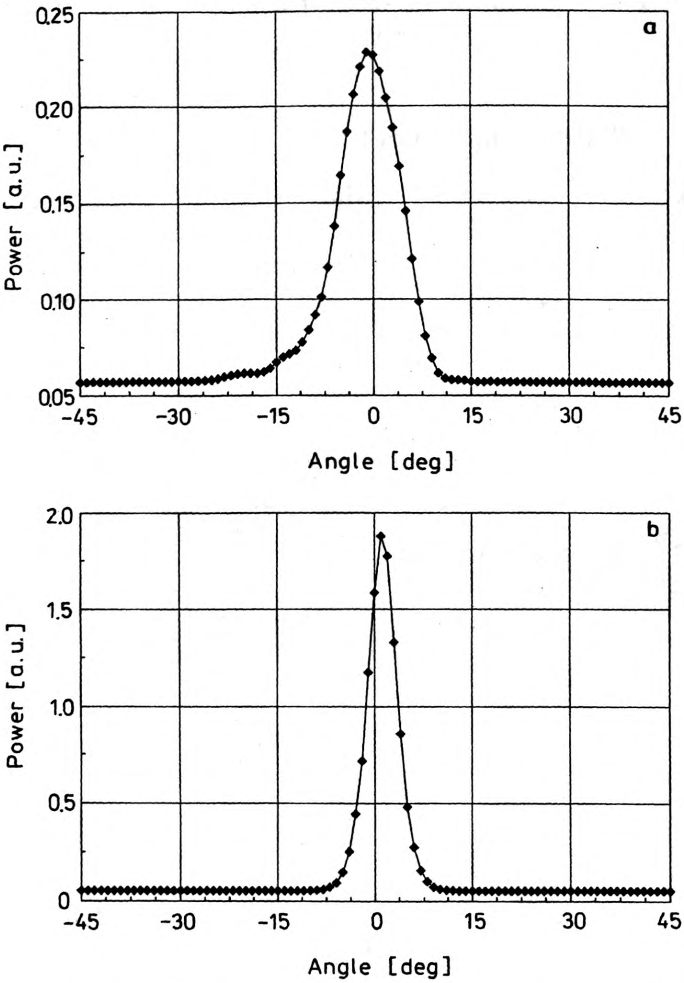

Fig. 2. Far field profile of the fiber lenses (a) and the flat end fiber (b) illuminated from the opposite end. **a** – $\Theta_{FWHM} = 11.10°$, spot size diameter of a focus = 4.2 μm, **b** – $\Theta_{FWHM} = 5.5°$, spot size diameter = 8.5 μm

measured by calculating the ratio of the external differential quantum efficiency of the fiber output power to that of the laser output. The location of the maximum coupling point in the axial direction is around 20 μm from the laser facet and depends on radius of the lens. It is further than that for the flat-end fiber, where the smaller distance between laser facet and fiber end gives higher coupling efficiency. Consequently, the danger of striking the fiber end against the laser during the assembly process is less with tapered fiber than with flat-end one. The angular tolerance is rather broad, which makes angular manipulation unnecessary in the actual assembly process.

The maximum coupling efficiency for different lasers changes between 33 and 67% and depends on fiber taper and lens losses, taper length and lens symmetry,

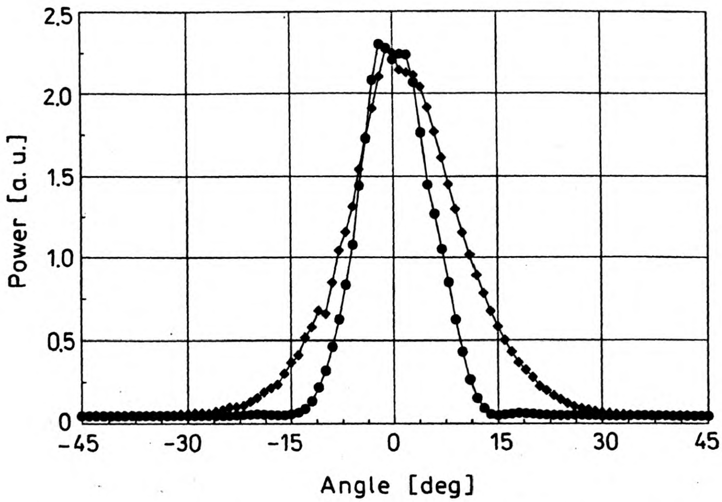

Fig. 3. Horizontal (●) and vertical (■) far field profile of the laser

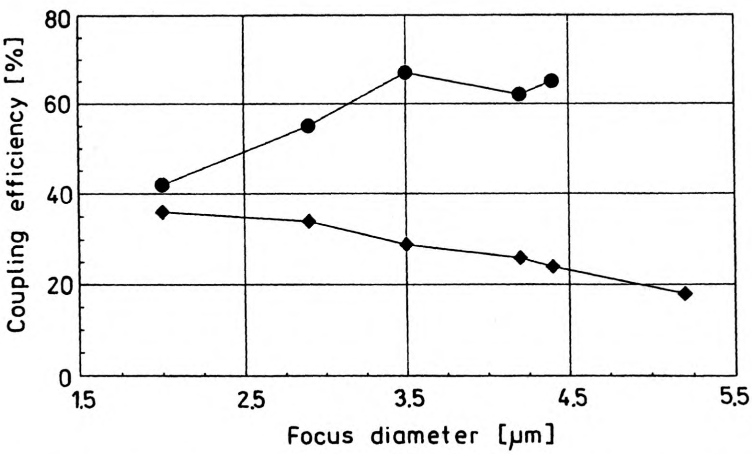

Fig. 4. Coupling efficiency dependence on the focal spot size diameter of the beam radiated from the fiber during the far-field experiment: (●) with laser of 17° × 23° beam divergence, (■) with laser of 24° × 48° beam divergence

compatibility of divergence angle of the laser beam and an angle of acceptance of the lens. It is possible to obtain 1.5 to 3 times more power coupled into the tapered end fiber than for the flat end one. Fn Figure 4 results of coupling experiments for two lasers are shown as a function of a spot size diameter in focus of the lenses (calculated from Θ_{FWHM}).

Measurements of a characteristic change of lasers due to reflected light, which is a significant problem in actual systems has also been reported [5], [6]. Because of the small radius of curvature there is a large divergence of light reflected from the hemispherical surface of the tapered lensed fiber. Therefore, the amount of light fed back from a tapered lensed fiber is much less than that from a flat-end fiber [7].

4. Conclusions

To obtain a tapered end with hemispherical lens a very simple process of pulling this fiber in the electrical arc is used. This tapered lensed fiber is obtained with good reproducibility by this method. Coupling efficiency from semiconductor lasers in the 1.55 μm range into a single mode fiber with tapered hemispherical end was significantly improved. Its optimum shape is around 15–25 μm curvature radius and 400–800 μm taper length. The coupling efficiency around 30–35% is usually possible to obtain. The maximum coupling point in the axial direction is located some distance from the laser facet, so the danger of striking the fiber end against the laser during the assembly process is less with tapered fiber than with flat-end one. Influences of reflected light, such as threshold current change, power fluctuation, and noise generation, are much smaller for tapered than for flat-end fibers.

Relative ease of fabrication, reasonable coupling efficiency and relatively reduced influence of the reflected light make the lensed fibers very attractive. They can find a lot of applications in sensor systems [8]. They can be used to strengthen the coupling not only between laser and fiber but also between fiber and other planar devices.

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