HIGH EFFICIENCY SOURCE COUPLING INTO SINGLE MODE OPTICAL FIBERS

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ABSTRACT

Coupling efficiency between a laser diode and a single mode fiber can be highly increased by using a chemically etched self-centred microlens on the end of the fiber. A gain by a factor of 4 over butt coupling has been obtained. A simple model, according to classical Gaussian optics theory, has been used to explain the results.

INTRODUCTION

The proper design of an optical communication system using optical fibers as the transmission medium requires a knowledge of the transmission characteristics of the optical sources, fibers, and its interconnections. The purpose of this paper is to investigate the coupling of energy from an optical source into fibers. Increasing of the source-to-fiber coupling directly increases the repeater spacing in long-haul transmission systems. The laser power that can be launched into a single mode fiber, by using the simple butt-joint method is small. This is because of the mode mismatch between the laser diode and the fiber. Hence, for high coupling efficiency, the laser diode mode must be transformed to match that of the fiber. This can be achieved by using a lensing scheme [1]. In this paper, we investigate theoretical and experimentally the use of chemically etched and self-centred microlens [2] as the light mode transformer between a laser diode and a single mode fiber.

SOURCE COUPLING INTO AN OPTICAL FIBER

The coupling of power from an optical source into a fiber is defined by the coupling efficiency

$$\eta = P_F/P_S \quad (1)$$

where P_F is the power injected into the fiber core and P_S is the output power of the source. The factors affecting η can be broadly divided into two categories [1]. The first category, loss due to unintercepted illumination, can be caused by the source's emitting area being larger than the fiber's core area. Unfortunately, the brightness of an image in the fiber core cannot exceed that of the source and so, an intermediate lens cannot "focus" all the light into the core. Even if the source is smaller than the core, one can still have problems with unintercepted illumination if separation and misalignment of the source and fiber axes allow emitted light to miss the core and become lost. Coupling loss due to unintercepted illumination can be eliminated, however, if the source-emitting area and the fiber-core area are properly matched and aligned. The second category of coupling loss that affects the efficiency of source-coupling into a fiber is due to mismatches between the source beam and fiber numerical apertures.

For fiber optic communication systems two types of light sources, light-emitting diodes (LEDs) and injection laser diodes (ILDs) are tipically used. To calculate the coupling loss due to numerical aperture mismatch, it becomes necessary to know the radiation characteristics of LEDs and ILDs. The radiation pattern obtained from an edge-emitting LED is elliptical in cross section with half-power beam divergence angles of approximately $\pm 60^\circ$ and $\pm 30^\circ$. The radiation pattern obtained from a double hetero-junction laser diode is also elliptical in cross section but narrower in beam width than an LED. For example, the half-power beam divergences of the ILD used in the experiments described later are 18% and 13% perpendicular and parallel to the junction plane, respectively (Fig. 1).

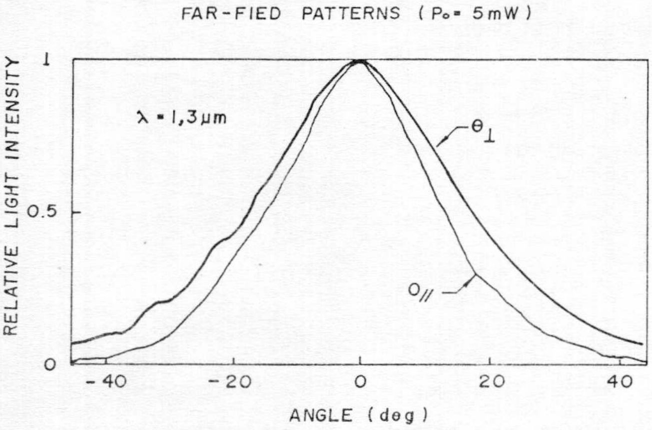

FIG. 1 - Far-field intensity pattern of ILD measured in planes parallel and perpendicular to the junction.

COUPLING EFFICIENCY USING A CONICAL LENS

We assume a single mode laser emitting an elliptical Gaussian beam having spot sizes a and b. The laser is located at z = 0 as seen in Fig. 2. A single mode fiber with a spot size c and a thin conical lens built on its end receives the light. The lens height is h and the core diameter is 2W. As seen in Fig. 2, the tip of the conical lens is located at z = H. A known relationship between W and c is assumed.

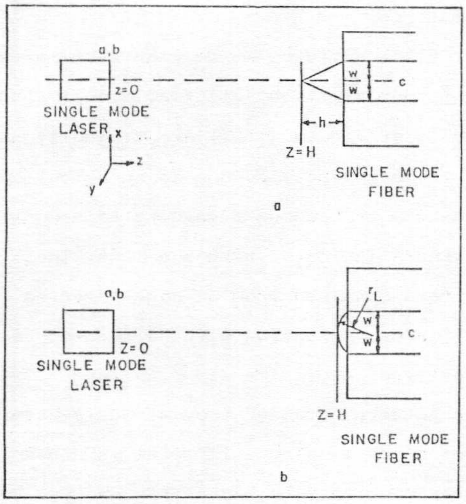

FIG. 2 - Schematics of laser to fiber coupling showing spatial parameters for (a) conical lens, and (b) hemispherical lens.

Let us calculate the evolution of the field radiated from the laser as it travels through the air, traverses the lens, and is coupled to the fundamental mode of the fiber. The field intensity of the fundamental mode radiated by the laser into free space is, according to classical Gaussian optics theory [3]

$$E_z = f_z \cdot g_z \qquad (2)$$

where

$$f_z = \left(1+i\frac{\lambda z}{\pi a^2}\right)^{-1/2} \exp\left\{-\frac{x^2}{a^2}\left(\frac{1+i\lambda z/\pi a^2}{1+(\lambda z/\pi a^2)^2}\right)\right\} \qquad (3)$$

and λ is the free-space wavelength. The expression for g_z is obtained from (3) substituting x and a with y and b.

Using the thin-lens approximation, the conical lens is assumed to act as a phase shifter. The transmission coefficients through the lens $(x^2+y^2)^{1/2} < W$ and through the air outside the lens $(x^2+y^2)^{1/2} > W$ are

$$T_1 = \exp\left\{i\frac{2\pi h}{\lambda}\left[\frac{n-1}{\lambda}(x^2+y^2)^{-1/2}-n\right]\right\} \text{for } (x^2+y^2)^{1/2} < W$$

$$T_2 = \exp\left\{-i\frac{2\pi h}{\lambda}\right\} \quad \text{for } (x^2+y^2)^{1/2} > W \qquad (4)$$

where n is the core index of refraction. The field arriving at the fiber is then

$$E = E_H T \qquad (5)$$

Since the field of the fundamental mode in the fiber, using the Gaussian approximation is

$$\varepsilon = \exp\left\{-\frac{x^2+y^2}{c^2}\right\} \qquad (6)$$

the coupling efficiency between the laser and the fiber is given by the following normalized overlap integrals [4]:

$$\eta = \frac{\left|\int_0^W dy \int_0^X \varepsilon E_H T_1 dx + \int_0^\infty dy \int_{Re\{X\}}^\infty \varepsilon E_H T_2\, dx\right|^2}{\int_0^\infty \int_0^\infty E_0^2\, dxdy \int_0^\infty \int_0^\infty \varepsilon^2\, dxdy} \qquad (7)$$

where $X \equiv (w^2-y^2)^{1/2}$ and Re $\{(w^2-y^2)^{1/2}\}$ means the real part.

The theoretical coupling efficiency for the general case of an arbitrary laser-fiber combination has been calculated including an optimization of the lens geometry (h/W) and the laser-fiber separation (H/W). The results for a symmetrical beam are shown in Fig. 3. The optimum coupling efficiency compared with butt coupling as well as the required h/W and H/W are shown for the case of a/c = b/c ranging between 0 and 1. In Fig. 3, c/W = 0.98 which is close to the value used in the experiments described later.

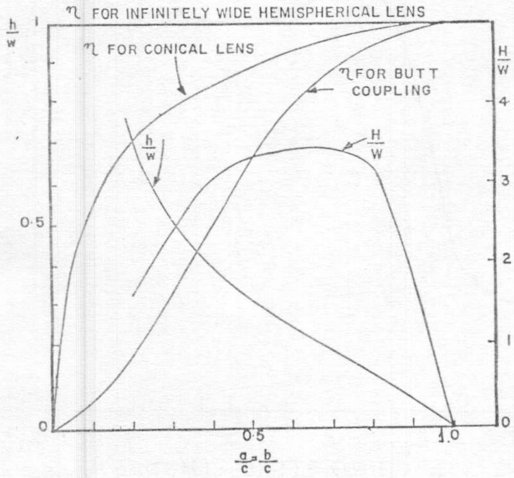

FIG. 3 - Coupling efficiency using a conical lens as a function of laser-to-fiber spot size ratio for a symmetrical beam. Optimum values for h/W and H/W are shown in the figure. Butt coupling is shown for comparison C/W = 0.98.

The conical lens, being circularly symmetric, cannot correct for the ellipticity of a nonsymmetrical beam. In such a case, the lens can at best match the fiber spot size to the geometrical mean of the laser spot size. For nonsymmetrical beams, then, coupling efficiency is a product of two factors [4]. The first can be found from the conical lenses in Fig. 3 by replacing a/c = b/c by $(ab)^{1/2}/c$. Optimum lens geometry, as well as the laser-fiber separation are also determined from Fig. 3. The second factor takes into account the ellipticity of the beam and is $M = 4ab/(a+b)^2$. We note that for ellipticity ratios above 0.53, the ellipticity factor M is higher than 0.9

COUPLING EFFICIENCY USING A HEMISPHERICAL LENS WHOSE WIDTH EQUALS THE FIBER CORE DIAMETER

Such a lens may be obtained in principle by fire polishing or arc melting the etched cone [2]. The calculation is similar to the one presented above [4]. The conical lens is replaced by a thin hemispherical lens whose radius of curvature is r_L as seem in Fig. 2b. The optimized coupling efficiency, as well as the optimum lens geometry r_L/W and the laser-fiber separation H/W, are shown in Fig. 4 for a symmetrical beam where c/W = 0.98. To examine the increase in efficiency achieved by this hemispherical lens over the conical lens we compare Figs. 3 and 4. We note that the spherical lens is more efficient, but that the increase in coupling efficiency is no more than 10% for all values of a/c = b/c.

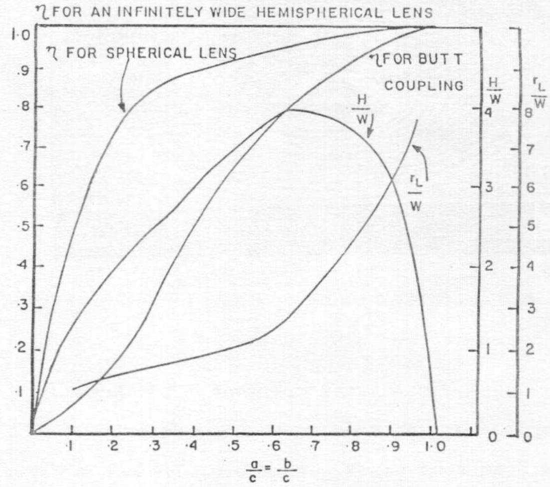

FIG. 4 - Coupling efficiency using a spherical lens as a function of laser-to-fiber spot size ratio for a symmetrical beam.

The efficiencies presented above are different if the ratio c/W is changed. For small values of c/W the lens is effectively wide and the coupling condition approachs that of an infinitely wide lens. If c/W is large enough, the condition of butt coupling is obtained. Maximum efficiency under both these extreme conditions is shown in Fig. 4.

EXPERIMENTAL RESULTS

The lens is manufactured by a selective chemical etch of the fiber [2]. The glass composition of the MCVD single mode fibers (Telebrás) used in this experiment is SiO_2-GeO_2 for core and pure SiO_2 for cladding. The chemical etchant used for selective etching is a buffered HF-1:9 mixture of 49% HF and 40% NH_4F solutions. The etching rate of the glass in this buffered HF is about 0.03 microns/min for pure SiO_2. Such rate was observed to decrease with increasing GeO_2 concentrations. The resulting lens is conical in shape and may be fire polished or arc melted into a hemispherical surface. Its base always equals the fiber core diameter. This lens has two major advantages: (1) it is easy to manufacture and is reproducible; it also allows batch processing; (2) it is automatically aligned with the fiber core as seen in Fig. 5.

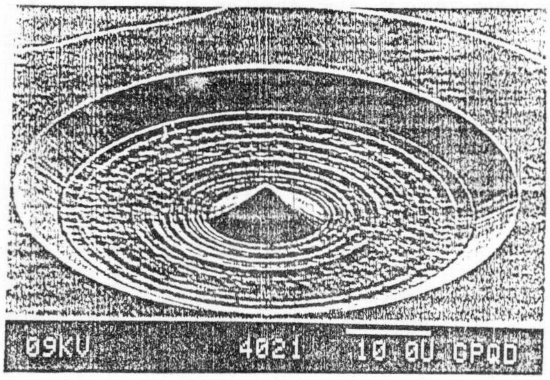

FIG. 5 - Chemically etched conical lenses on a single mode fiber. h/W = 0.8.

A 1.3μm Fujitsu crescent (CVS) heterostructure laser was used in the experiments. The infered beam spot sizes were a = 0.63μm and b = 0.9μm. Hence, a/b = 0.7 and $(ab)^{1/2}/c = 0.17$. According to Fig. 3, the calculated coupling efficiency is approximately 67%, and the ellipticity factor is M = 0.97, which reduces the coupling efficiency to 65%. Minimum Fresnel losses would drop this number below the level of 60%. The experimental results for the coupling efficiency are shown in Fig. 6 as a function of etching time. One can observe from the figure that the maximum coupling efficiency is around 62%. It is important to notice that maximum coupling was observed using a cone-truncated lens. Etching times longer than 2.5 hours lead to totally conical lens having coupling efficiencies of 55%. These results are predicted by the present model. Cone-truncated lens closely resembles the spherical shape, which according to the model provides better coupling to the fiber.

The calculated butt-coupling efficiency is 12%, which agrees, within the experimental error, to the measured value. According to Fig. 3, the required lens should have h/W = 0.88 which is close to the value used in the experiment (h/W = 0.8). An optimum working value of H/W = 1.3 was set for maximum coupling which meets to the predicted ratio. The experimental c/W ratio was around 1.1, somewhat above the value used in the calculations (c/W = 0.98).

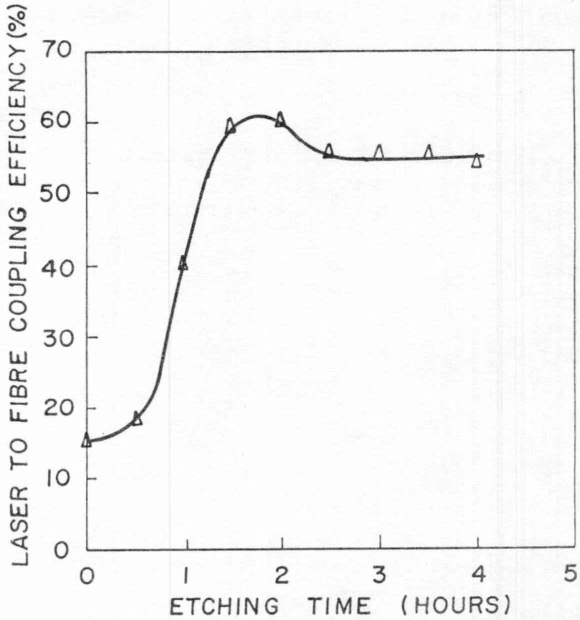

FIG. 6 - Coupling efficiencies as a function of etching time for a single mode fiber.

CONCLUSIONS

It is presented a theoretical design of both conical and hemispherical microlenses, whose widths coincide with the core diameter. Maximum coupling efficiency as well as the optimum lens geometry and laser-fiber separation have been both calculated and measured. Using these lenses, the optimum working distance is always finite which avoids the need to bring the laser and fiber into close physical proximity. We conclude that the use of these simple lenses improves the coupling efficiency from the 15% observed for butt-coupling up to 62%. The theoretical model predicts that an extra 5% coupling might be obtained by using anti-reflecting coating on the lens surface.

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