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Measurements of Loss Due to Offsets and End Separations of Optical Fibers

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If fibers are to be coupled together by means of detachable connectors, there is a need to know how much light will be lost by misalignment or axial separation of the fiber ends.

Measurements were made of coupling efficiency from one fiber to another versus offset and end separation with and without index-matching liquid between the ends for a single-mode and a multimode fiber at $\lambda = 0.6328$ *μm. Graphs are presented for offsets as great as 3 radii and for end separations up to 127 μm. Maximum coupling efficiency of 97 percent was obtained, and about 50 percent was obtained with an offset of 1 radius.*

I. INTRODUCTION

Coupling of glass fibers, end to end, for transmitting optical signals requires critical alignment at each coupling point. Coupling can be accomplished by permanently fusing the fibers together,[1] by using permanently bonded sleeves, or by using detachable connectors.

This paper presents experimental data for the coupling efficiency of light from one fiber end into another as a function of offsets and axial separation which will be present in detachable connectors and to a lesser extent in fused joints and sleeve joints.

Measurements of coupling efficiency versus end separation and translation were made and plotted for a multimode fiber with core diameter of 10.8 μm and a single-mode fiber with a core diameter of 3.7 μm.*

Several people[2,3,4] have studied the problem of launching efficiency from a Gaussian beam into a fiber, both theoretically and experimentally. A comparison will be made between the theory and our experimental data.

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* The 10.8-μm core fiber was manufactured by DeBell and Richardson, Inc., of Hazardville, Connecticut, and the 3.7-μm core fiber was made by Corning Glass Co.

II. EXPERIMENT

2.1 *Equipment*

Figure 1 is a sketch of the measuring apparatus. The light from a He-Ne laser operating in the single transverse TEM_{00} mode that gives a Gaussian distribution was chopped, then focused down by a 10X microscope objective into a fiber that we call the launching fiber. The output end of the launching fiber was mounted on a precision 3-dimensional micromanipulator with positioning resolution of 0.127 μm. The output of this fiber was launched into a fiber that we call the receiving fiber. The output of the receiving fiber was detected by a solar cell immersed in index-matching liquid, measured by a lock-in amplifier, and recorded on a chart recorder. Mode strippers (not shown) were used on both launching and receiving fibers to eliminate the light traveling in the cladding. These were made by cutting an S-shaped groove about 0.25 mm wide and deep in a piece of plexiglass about 30 cm long and placing the fiber in the groove, then filling it with index-matching oil of a slightly higher index than the fiber cladding. None of these dimensions are critical, and the same effect could probably be obtained by making the stripper much smaller.

2.2 *Method*

(*i*) Coupling efficiency versus fiber end separation was measured by first aligning the fiber ends axially and then bringing them into contact

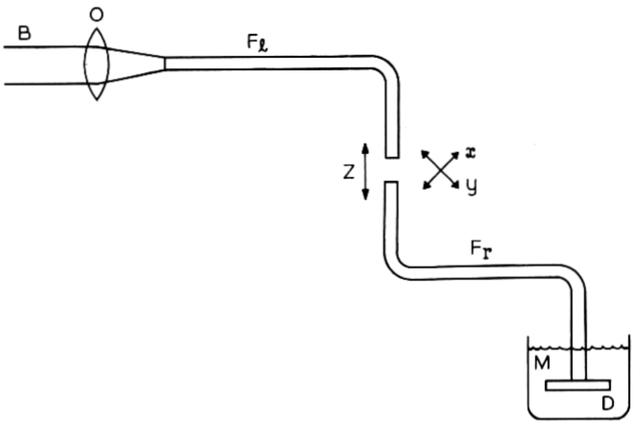

Fig. 1—Schematic diagram of light coupling measuring apparatus: B, chopped beam from laser; O, microscope objective; F_l, launching fiber; F_r, receiving fiber; M, index-matching oil; D, detector.

with each other for the measurement at zero separation. One fiber was then separated from the other by known amounts and the output of the receiving fiber was recorded. This was repeated several times for each case and the mean of the readings was plotted. These measurements were made for the 10.8-μm and 3.7-μm-diameter core fibers with and without index-matching oil in the gap. A reliable measurement could not be made at zero separation without oil because of interference effects.

(*ii*) Coupling efficiency versus fiber lateral displacement was measured and plotted for both fibers with and without matching oil between them. These measurements were made for fiber end separations of 5.08 μm, 10.16 μm, 25.4 μm, and 50.8 μm. The smallest separation for which scanning measurements were made was 5.08 μm because they could not be made at zero separation as one fiber would rub against the other, and also because of the interference effects mentioned above. In each case the scanning was begun with the fibers out of alignment on one side of the fiber axis so as to give approximately zero transmission, then one fiber was translated past the axis of the other reaching a maximum transmission, and continuing on until approximately zero transmission was reached again. This operation was repeated four times, once each in the plus and minus x and y directions of Fig. 1 for each separation. The mean of these four readings was then plotted.

(*iii*) The coupling efficiency expressed in percent was calculated from the power levels measured at the ends of the launching and receiving fibers and from the transmission loss in the second fiber. Absolute values of the data presented could be in error by as much as 3 percent.

2.3 *Results*

2.3.1 *Multimode* 10.8-*μm-Diameter Core Fiber*

For this fiber $r = 5.4$ μm, $\lambda = 0.6328$ μm, the core index is 1.6171, and the cladding index is 1.6038. From this data we find that the fiber is capable of propagating 67 modes.[5]

It would be difficult to mathematically predict the light coupling loss due to offsets or fiber end separation from such a multimode fiber, so no comparison was made between theory and experimental data on this fiber.

The coupling efficiency at 2.54-μm separation without oil in the gap was measured to be 88.8 percent, and at zero separation with oil in the gap it was 97.06 percent. These values appear as points on the curves of Fig. 2. The data in graph B was taken with index-matching oil

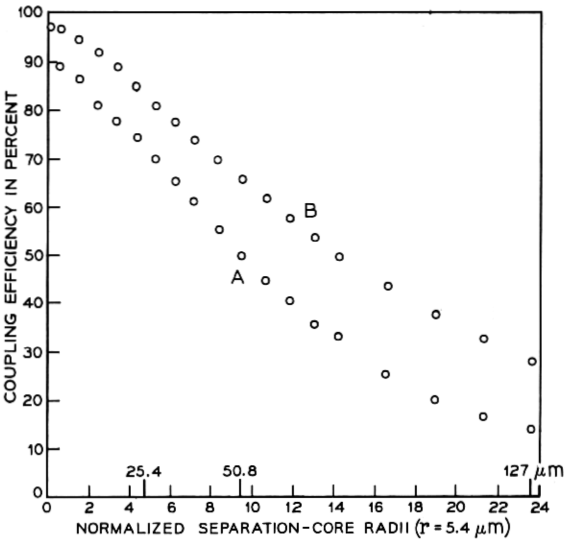

Fig. 2—Curves of coupling efficiency versus fiber end separation for 10.8-μm -diameter core fiber: A, without index-matching oil in the gap; B, with matching oil in the gap.

($n = 1.6204$) in the gap between the fiber ends, and in graph A without oil. A reliable reading could not be taken at zero separation without oil in the gap because of the interference between the transmitted and reflected beams between the plane parallel surfaces of the fiber ends, but all the readings for each graph at 2.54-μm (approximately 0.5 radius) separation were within ±0.5 percent of each other.

The Fresnel reflection loss at the two core-air interfaces is 11.2 percent (neglecting resonance effects). If we subtract this from 100 percent we get 88.8 percent which is the coupling efficiency that was measured at 2.54-μm separation without oil in the gap. This implies that all the light except that reflected is coupled into the receiving fiber.

When oil of index $n = 1.6204$ was put between the fiber ends eliminating the core-air interfaces, the amount of light coupled increased by about 8 percent to 97 percent, which was less than the 11.2 percent increase predicted.

Figure 3 shows the coupling efficiency versus offset for four different fiber end separations without index-matching liquid in the gap. Figure 4 has the same set of curves with index-matching oil in the gap.

We see that only 50 percent of the light is transmitted with perfect axial alignment for fibers separated by 50.8 μm without matching oil

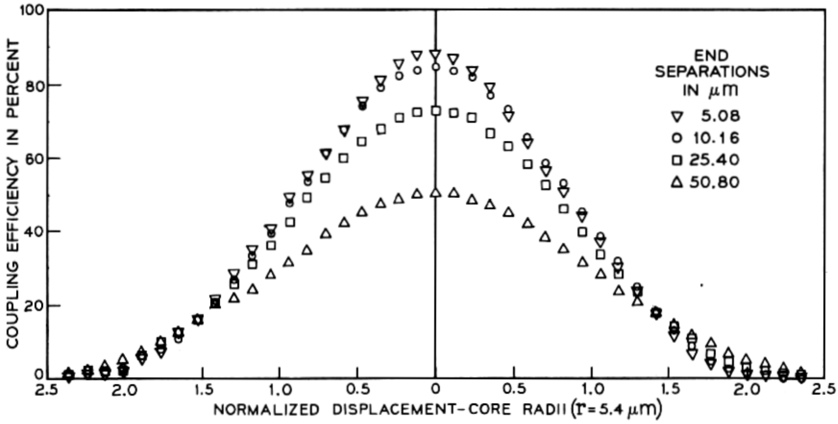

Fig. 3—Coupling efficiency versus displacement of 10.8-μm-diameter core fiber without index-matching oil in the gap.

between them. It can be seen also that all the curves are coincident at about 20 percent efficiency at a little less than 1.5 radii translation both with and without index-matching liquid in the gap.

2.3.2 *Single-Mode 3.7-μm-Diameter Core Fiber*

For this fiber, the fiber characteristic term[6]

$$R = \frac{2\pi a}{\lambda} (n_1^2 - n_2^2)^{\frac{1}{2}}$$

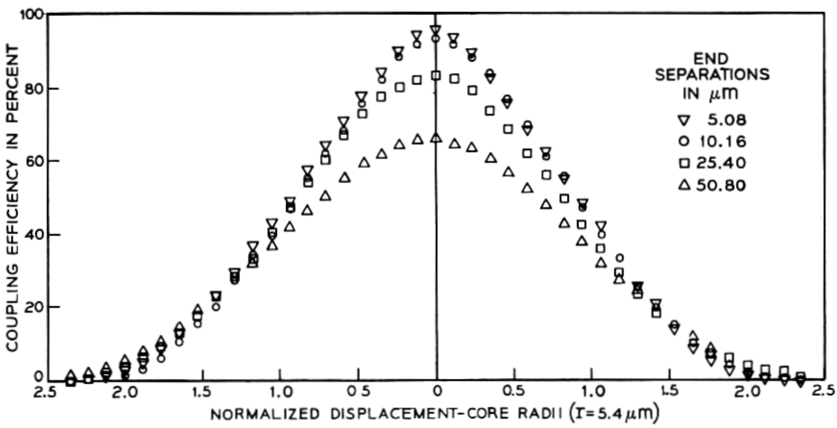

Fig. 4—Coupling efficiency versus displacement of 10.8-μm-diameter core fiber with index-matching oil in the gap.

is 2.2 at $\lambda = 0.6328\ \mu$m, where a is the radius of the core, n_1 is the refractive index of the core, n_2 is the index of the cladding, and λ is the wavelength of the light. Only the HE_{11} mode can propagate because all other modes are cut off in a fiber with $R < 2.405$.

Coupling efficiency versus fiber end separation is plotted in Fig. 5. The coupling efficiency at 2.54-μm separation without oil in the gap was found to be 90 percent. This is shown in curve A, and when this curve is extrapolated to zero separation, we find the coupling efficiency at zero separation is approximately 91 percent. This compares with 90 percent for the multimode fiber at zero separation without oil. With oil in the gap at zero separation the coupling efficiency was 97 percent. Thus, the matching oil increased efficiency by 6 percent. This is the same efficiency as was found for the multimode fiber with oil in the gap at zero separation.

There are no striking differences between the coupling efficiency versus fiber end separation curves of the two fibers which are shown in Figs. 2 and 5. It has been noted that at zero separation the efficiencies are virtually the same, but at 127-μm separation, which is almost 70 radii for the 3.7-μm-diameter core fiber though less than 24 radii for the 10.8-μm-diameter core fiber, we see some small differences. Without oil at this separation the 10.8-μm core fiber has 14.5 percent efficiency and the 3.7-μm core fiber has 13 percent showing the multimode fiber more efficient by 1.5 percent. With index-matching oil at this separation, coupling into the single-mode fiber is more efficient by 5 percent, than into the multimode fiber. At about 50-μm separation both with and without oil in the gap, coupling efficiency is about 10 percent less in the single-mode fiber than in the multimode fiber.

Figures 6 and 7 show curves of coupling efficiency versus fiber translation for the single-mode fiber. Figure 6 shows curves of coupling efficiency versus fiber translation for four end separations without matching oil in the gap and Fig. 7 shows the same curves with oil in the gap. These curves are comparable to the corresponding ones for the multimode fiber in Figs. 3 and 4, except for the above-noted lower efficiency for the single-mode fiber at greater end separations. We see also that the efficiency does not drop to zero as quickly with respect to displacement with the single-mode fiber as with the multimode one. This is understandable in that with the single-mode fiber, the field extends into the cladding, but in the other fiber the field is rather sharply restricted to the core.

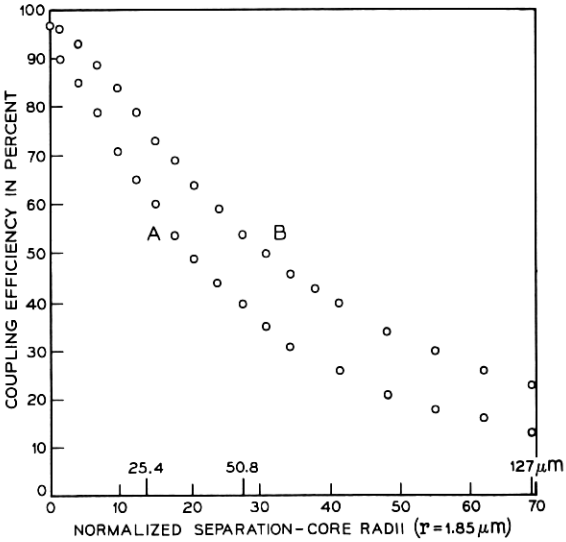

Fig. 5—Coupling efficiency versus fiber end separation of 3.7-μm-diameter core fiber: A, without index-matching oil in the gap; B, with index-matching oil.

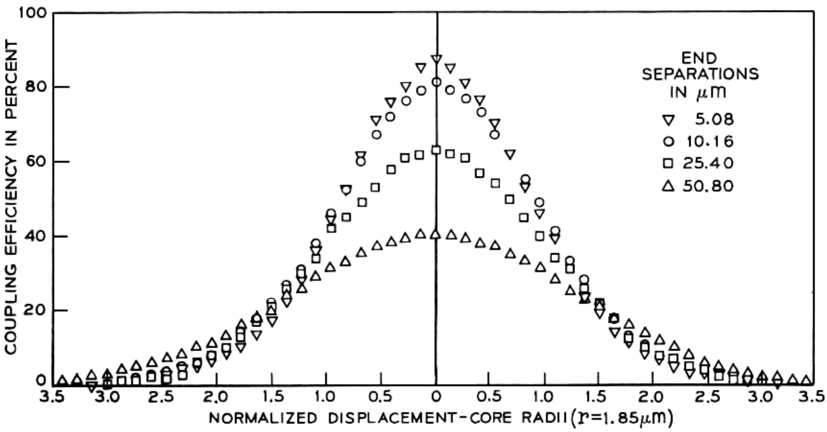

Fig. 6—Coupling efficiency versus displacement of 3.7-μm-diameter core fiber without index-matching oil in the gap.

III. COMPARISON WITH THEORY

In the absence of irregularities such as nonflat fiber ends and index mismatch, the coupling efficiency from one fiber to another at zero separation should be 100 percent.

Launching efficiencies of nearly 100 percent for the HE_{11} mode from an incident Gaussian beam have been predicted theoretically by J. R. Stern and R. B. Dyott,[2] and D. Marcuse.[3] The field profile of the HE_{11} mode is similar to a Gaussian distribution, thus the theory which predicts the launching efficiency from a Gaussian beam into a fiber should approximately predict the coupling efficiency from our single HE_{11} mode launching fiber into the corresponding receiving fiber. Marcuse calculated the theoretical curve of coupling efficiency versus translation in Fig. 8 using the parameters of our single-mode fiber. The experimental data for our fiber with index-matching oil in the gap at 5.08-μm separation was modified to represent a curve of zero separation and is plotted in Fig. 8 for comparison. At the top of the curve we launched only 97 percent of the incident light where theoretically almost 100 percent could have been launched. In the middle the curves are coincident and at the lower end the discrepancy between the curves is probably due to the fact that the edge of the HE_{11} mode is not well approximated by the Gaussian beam.

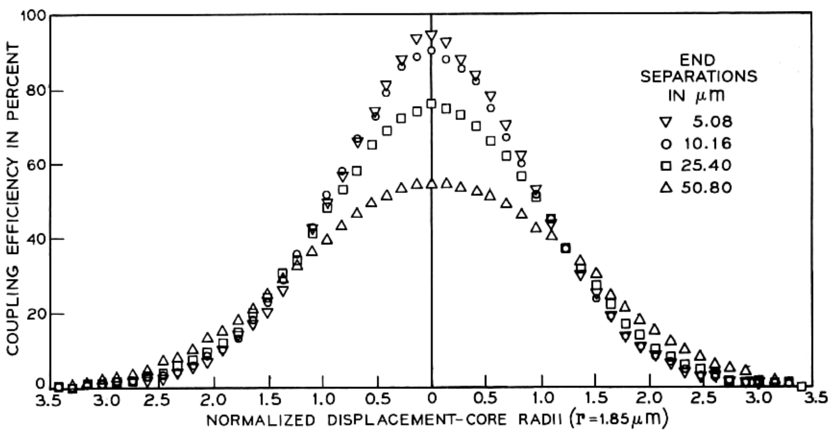

Fig. 7—Coupling efficiency versus displacement of 3.7-μm-diameter core fiber with index-matching oil in the gap.

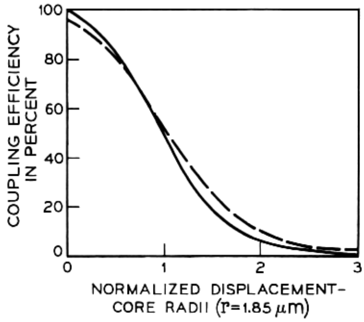

Fig. 8—Coupling efficiency versus translation of 3.7-μm-diameter core fiber: solid line is theoretical, broken line experimental.

IV. CONCLUSIONS

With matching oil in the gap between two fiber ends with zero separation, 97 percent of the light from one fiber was coupled into the other in either single-mode or multimode fibers. The light coupled from a single-mode fiber into another single-mode fiber follows closely the theory for light coupled from a Gaussian beam into a single-mode fiber when one fiber is offset with respect to the other. For fiber ends separated up to 25 μm, a lateral displacement of one radius reduces the coupling efficiency to about 50 percent if there is index-matching liquid between the fiber ends, and to about 40 percent if there is none. The coupling efficiency was reduced by 10 percent with end separation of about 3 radii for the multimode fiber and about 7 radii for the single-mode fiber.

V. ACKNOWLEDGMENT

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