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Simple, Low-Loss Joints Between Single-Mode Optical Fibers

By C. G. SOMEDA*

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Low-loss joints between single-mode optical fibers have been made without microscopic alignment, without fusing the tips, and without monitoring the transmitted power while the joints are assembled. The fibers are tightly held in an embossed groove; an index-matching liquid is added. Average power coupling efficiencies close to 90 percent in the red and to 85 percent in the infrared have been obtained. Mediocre end faces are acceptable. Realistic discrepancies between the fiber cladding diameters (slightly in excess of twice the core diameter) do not deteriorate the results.

I. INTRODUCTION

Recently, several authors have dealt with techniques for making low-loss joints between multimode[1–4] or single-mode[5] optical fibers. For long-distance communication channels, joints between fiber cables, simply assembled in the field, would be very valuable.

The joints that were made so far with the technique described in this paper connected just one pair of fibers at a time. However, this is intended to be the first step in the development of joints between multifiber cables. Therefore, in the present experiments emphasis has been put on getting repetitive results which are not a consequence of careful laboratory adjustment. This is an important difference with respect to the methods that gave the best results reported so far.[1,5] Nonetheless, the joints between single-mode fibers described here compare favorably with previous ones as far as the losses are concerned. The demonstration with single-mode fibers (core diameters of $\approx 4\ \mu m$) means that the technique applies also to multimode fibers, the larger core diameters of which should make the alignment less critical.

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* This work was performed at Bell Telephone Laboratories, Incorporated, Crawford Hill Laboratory, Holmdel, New Jersey, during a six-month internship sponsored by a NATO–CNR fellowship.

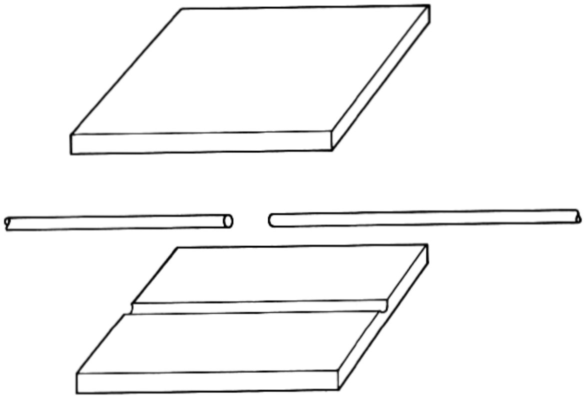

Fig. 1—View of the unassembled parts of a sandwich joint.

A complete description of the technique follows in Section II. As a rough sketch, we may say that the tips of the fibers are aligned in a groove (Fig. 1), embossed in a Plexiglas sheet.* The fiber tips are pushed against each other. An index-matching liquid is added. A "sandwich" is formed with a flat Plexiglas sample, and then squeezed by means of a small vise (Fig. 2). No fusion takes place and no microscopic alignment is needed.

It is obvious that the fiber claddings are aligned in this way and therefore the results depend on the fiber core being coaxial with the cladding. The experiments reported here were performed with single-mode fibers† having a core diameter of 3.7 μm and a cladding diameter of 254 μm; coincidence of the core and cladding axes within ≈1 μm had been observed preliminarily.

Experiments were performed at 6328 Å and at ≈9000 Å. Repetitive measurements gave average power couplings around 87 percent in the red and around 83 percent in the infrared; best results were 93 percent and 87 percent, respectively. These figures were obtained without paying any particular attention to the quality of the end surfaces of the two fibers.

The experiments were completed by testing the effects of a difference, d, between the cladding diameters, as described in Section IV. It turned out that sandwiches of good mechanical quality exhibit no deterioration of the results for $d \cong 10$ μm (i.e., more than twice the core diameter). For $d \cong 30$ μm, the results were deteriorated, but still showed

* Plexiglas (methyl methacrylate), registered trademark of Rohm and Haas.
† These fibers were manufactured by Corning Glass Works, Corning, N. Y.

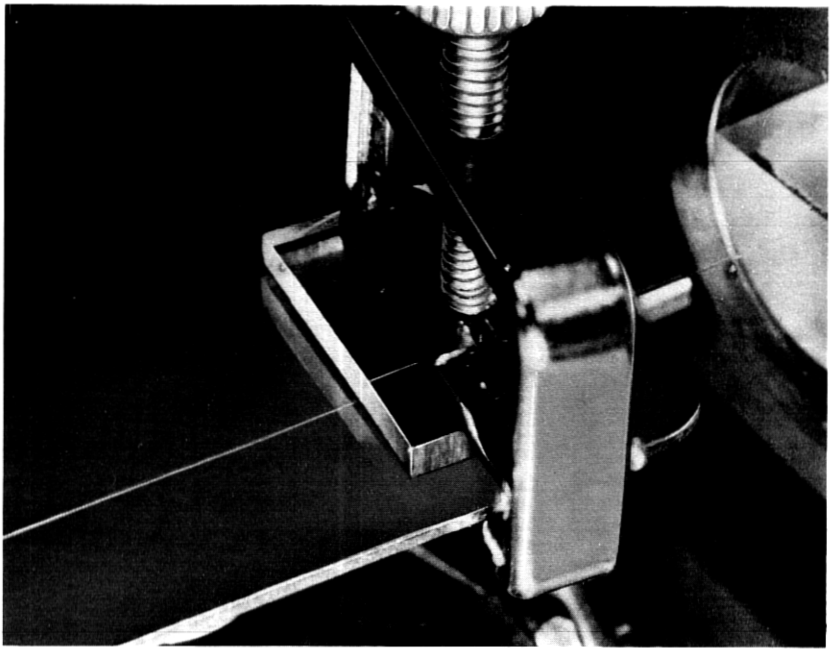

Fig. 2—View of an assembled joint. The length of the visible side of the sandwich, perpendicular to the fiber, is ≈2 cm.

the presence of an alignment mechanism, which is believed to be due to surface tension in the index-matching liquid.

II. DESCRIPTION OF THE JOINING TECHNIQUE

In order to obtain a joint of the type shown in Fig. 1, the first operation to perform is to emboss a Plexiglas sheet with a groove that fits the dimensions of the fibers to be joined.

A simple and economical technique for embossing grooves in a thermoplastic substrate by means of a glass fiber has been reported by Ulrich *et al.*[6] A further simplification of this procedure proved successful; there is no need to heat the substrate. A rectangular Plexiglas sample and a fiber piece, the length of which slightly exceeds the Plexiglas size, are put between two milled aluminum blocks (flat within ±1 mil) and then tightly pressed by means of a vise for a few minutes. When the vise is released, the fiber separates from the Plexiglas, leaving a sharply embossed groove. Any other piece of a nominally equal fiber can be introduced into the groove and fits it very closely. Figure 3

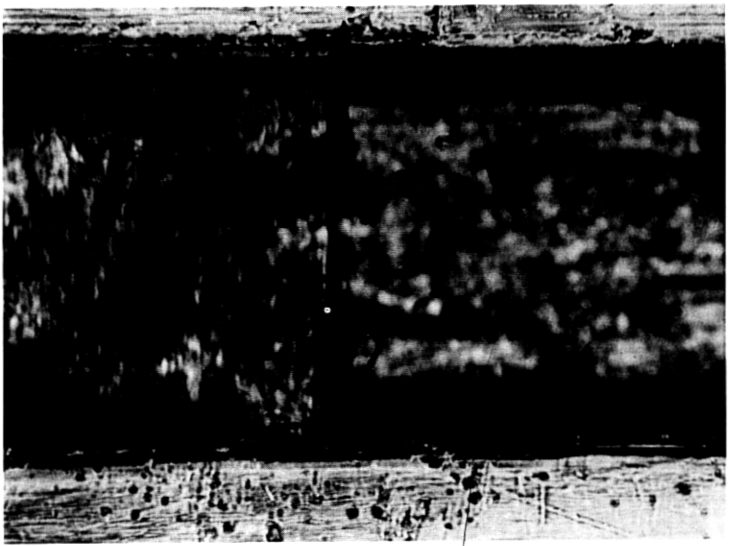

Fig. 3—Microscopic picture of a single-mode fiber tip (on the left) lying in an embossed alignment groove. Magnification 200× (1 cm in the picture is 50 μm in actual scale).

is a microscopic picture (magnification 200×) of a fiber tip lying in a groove, embossed with another fiber. Figure 4 is a further enlarged view (magnification 500×) of the groove edge in the vicinity of the fiber end; it shows no defect comparable to the size of the fiber cores to be aligned. It also shows a fairly regular pattern of longitudinal wrinkles due to the compression of the Plexiglas sample.

First, Plexiglas having a nominal thickness of $\frac{1}{16}$ inch was embossed with quartz fibers, 254 μm in cladding diameter. The samples were permanently curved with a remarkable convexity of the embossed side. The cover (Fig. 1) then tended to flip. Using a thicker Plexiglas sample (e.g., $t = \frac{1}{8}$ inch), the curvature was negligible.

There is some evidence that the deformation of the embossed Plexiglas sheets is elastic (at least partially) with a long time constant. Therefore, the joints have to be made with newly embossed samples, or with samples where a fiber has been constantly pressed in.

To assemble a joint, the fibers are put in the groove, a small amount of a suitable index-matching oil is added, and the cover is placed on top. At first, the top is not pressed against the bottom. Next, one fiber is pushed against the other in the axial direction; finally, the sandwich is squeezed with a small vise.

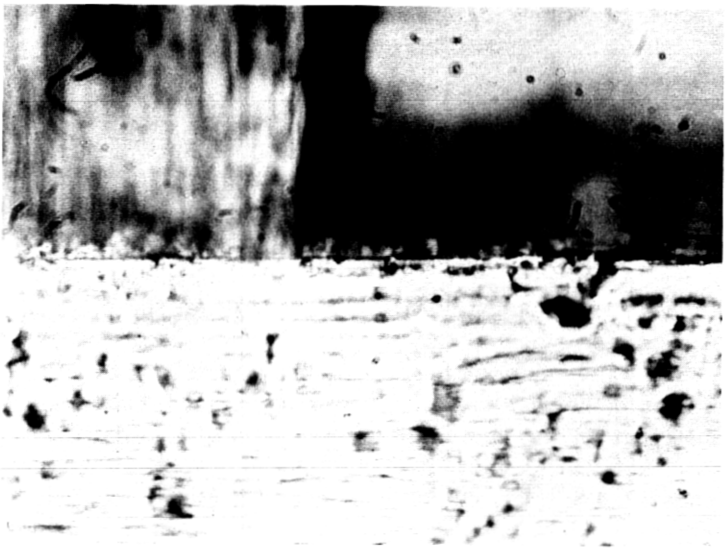

Fig. 4—Microscopic picture of the edge of a groove, with a fiber tip on the left. Magnification 500× (1 cm in the picture is 20 μm in actual scale).

It seems that the index-matching oil is rather slow in wetting the fiber tips, and some time is required for air bubbles to escape. The oil also has the purpose of lubricating the fiber longitudinal motion. Sometimes an excess of it deteriorated the joint performances, probably because an unwanted axial movement of the fiber tips was produced by the oil flux when the sandwich was squeezed. However, the presence of a small amount of liquid is needed in order to get good coupling efficiency (see Section 3.2). Furthermore, the presence of the fluid is believed to be responsible for the excellent behavior in case of unequal diameters of the two fibers (Section IV).

The amount of light transmitted by the joint does not always increase with increasing vise pressure. Often, though, a decrease in the coupling beyond a certain pressure was interpreted as due to some misalignment caused by careless movements accompanying the vise tightening. When the groove was deep enough and the top could not swing or slide, then such a decrease in transmitted power was absent or negligible. A good rule is to press the joint between surfaces that are not too stiff, so that the force is distributed on the whole area of the sandwich.

III. MEASUREMENTS

3.1 *Tests at 6328 Å*

Sandwich joints of the type described in Section II were tested first at the wavelength $\lambda = 6328$ Å. Based on manufacturer's data, the corresponding normalized frequency,[7] $V \cong 2.2$, means that single-mode propagation takes place. Direct observation of the far field at the end of a fiber confirmed that.

The set-up is illustrated in Fig. 5. The light emitted by a commercial He-Ne laser was chopped and then launched into the input fiber by means of a microscope objective (magnification 40×). A curved part of the fiber was lying in an index-matching liquid, to strip off the light launched into the cladding. The length of this mode-stripping section was such that any further addition or small subtraction did not affect the power level at the output of the fiber. This output was detected by means of an Si solar cell and the signal was sent to a lock-in amplifier. Figure 5 shows both arrangements that are needed in order to evaluate the insertion loss of a joint: a "reference" arrangement, where the detector is directly connected to the input fiber, and a "measurement" arrangement, where a joint and an output fiber are added.

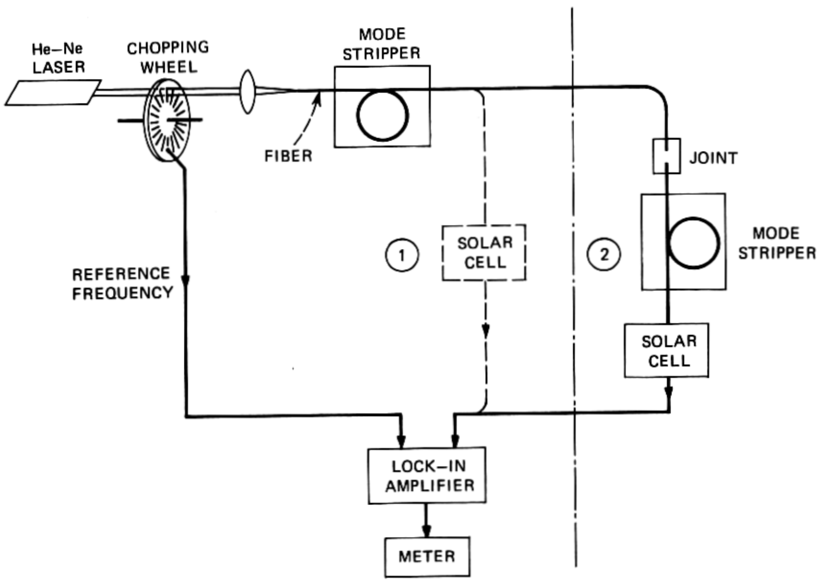

Fig. 5—Block diagram of the set-up used for the measurements at 6328 Å. The broken lines (Part 1) refer to calibration (measurement of a reference level). The solid lines (Part 2) refer to the actual measurement of the light transmitted through a joint.

Table I—Power Coupling Efficiencies Measured at 6328 Å and Corresponding Insertion Losses of the Joints

Sample Number	1	2	3
Best results	92% (0.35 dB)	93% (0.3 dB)	92% (0.35 dB)
Worst results	74% (1.3 dB)	80% (1.0 dB)	81% (0.9 dB)
Average results	80.7% (0.9 dB)	88.7% (0.5 dB)	86.6% (0.6 dB)
Number of measurements	12	6	6
Number of different ends	4	2	2

Attenuations measured in this way result from both the joint insertion loss and the losses in the output fiber. Previous data[8] and direct observation show that the output fiber attenuation is negligible with respect to the loss in the joint, despite the need for a length of the output fiber that could insure an effective stripping of all the light transferred by the joint into the cladding.

This way to perform the measurements was preferred to that where, after taking a reference, the fiber is cut and then joined again, because frequent checks of the reference were needed. Indeed, launching into a single-mode fiber is so critical (the power drops by 3 dB if the fiber tip is misaligned by a few microns), that accidental causes can produce strong shifts in the reference level. For example, in our case the material used to bind the fiber tip on an x-y-z manipulator could deform slowly, under the strength applied by the curved and quite elastic fiber. This effect was compensated for by optimizing the alignment of the fiber with respect to the incoming beam before any meter reading, both in the reference and in the measurement arrangements. Discrepancies between optimized reference levels monitored before and after a measurement were never larger than 3 percent and usually much smaller than that. When the reference levels monitored before and after a measurement were different, the more pessimistic estimate of the joint losses was taken.

Table I contains the best, worst, and average results of three sequences of measurements. As for the "worst" results, they exclude only those instances where clearly identified man-made mistakes took place; i.e., axially separated fibers, one fiber lying out of the groove, and Plexiglas debris shaved by the fibers and accumulated between the two ends. These errors were very rare, and were easily detected because of a large amount of scattered light shining from the sandwich. This point will be discussed further in Section 3.2.

The sequences of Table I refer to assembling, several times, joints that make use of three embossed grooves, one in a $\frac{1}{16}$-inch-thick plate and two in $\frac{1}{8}$-inch-thick plates. All the measurements were independent, in the sense that after any of them the joint was at least disassembled completely and then reassembled. The ends of the fibers were changed often, as shown in Table I. The amount of index-matching oil was changed quite often too.

An important point is that none of the measurements were of a joint where the two coupled end faces resulted from one cut of a fiber; they always resulted from two independent breaks, in order to simulate real situations.

A remarkable advantage of this technique is that there is no need for very accurate flatness of the fiber end faces. As long as there are no lips, which would prevent the two cores from getting close to one another, results are good. Figure 6 is a microscopic picture of one typical pair of ends used in the measurements. Attempts to get end surfaces of this

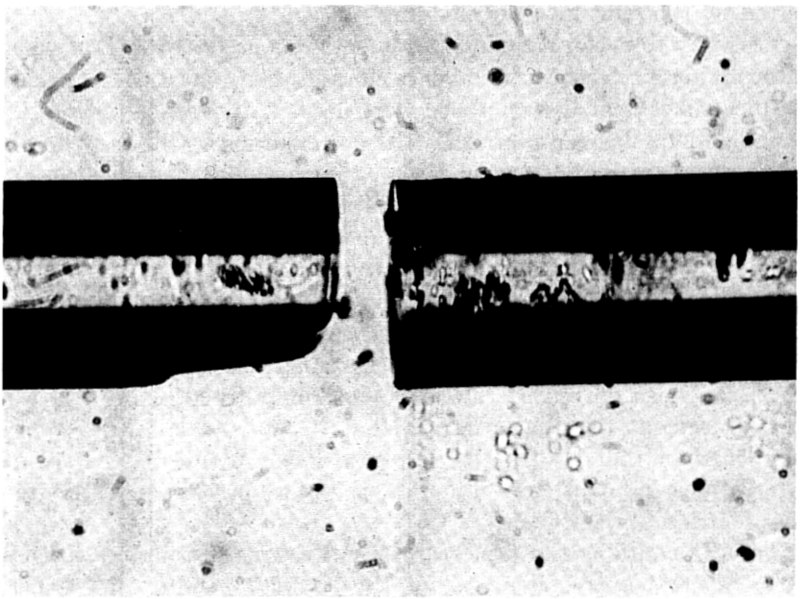

Fig. 6—Microscopic picture of a typical pair of fiber ends used in the sequence of experiments summarized in Table I. The bright zone in the center is not the fiber core, but just a consequence of the illumination.

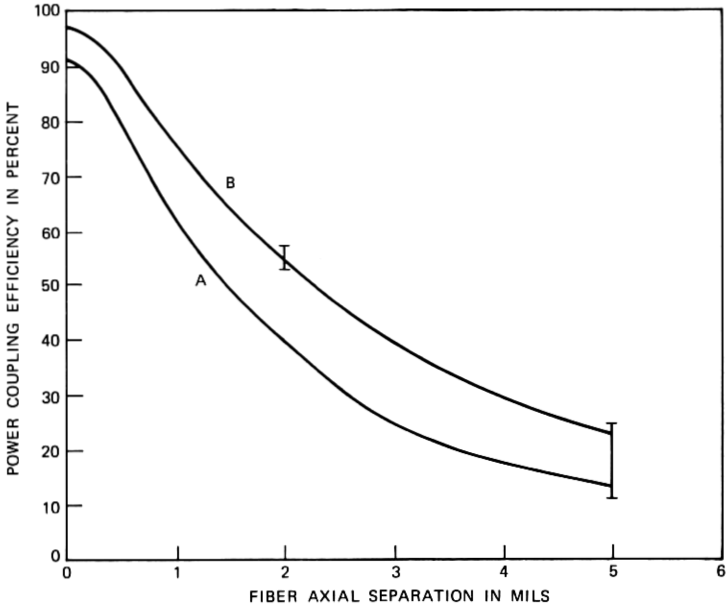

Fig. 7—Effects of the longitudinal separation between the fibers on the coupled power. Lines A and B, from Ref. 2, represent measured values (without and with index-matching oil, respectively) at 6328 Å when the fibers were aligned by means of micromanipulators. The vertical segments represent the range of results obtained when the fibers were held in a sandwich joint.

quality were almost always successful if the fibers were pulled after scoring them with a lathe tool or with an electrical discharge generated by a Tesla coil. Many successful attempts simply consisted of clamping the fibers in a Plexiglas sandwich and then pulling them. Consequences for the multifiber case will be stated in Section V.

Another interesting observation was that when a joint was tightened, bringing the fiber cores into alignment, the forward scattered light on the side surface of the output fiber decreased very remarkably.

Some additional measurements were performed in order to establish the effects of longitudinal separation between the fibers. The results are compared with those obtained by Bisbee[2] in Fig. 7. The very large spread of values observed for a 5-mil separation can be justified by an occasional shortage of index-matching oil, which could cause an air gap sometimes to show up when the fibers were separated; or by deviations of the groove from a rectilinear shape, which would cause unwanted transverse displacements of the fiber tips to accompany the longitudinal ones. The best results ($\eta \cong 56$ percent for a 2-mil separation,

TABLE II—POWER COUPLING EFFICIENCIES MEASURED AT 9000 Å AND CORRESPONDING INSERTION LOSSES OF THE JOINTS

Sample Number	2	3
Best results	87.5% (0.55 dB)	87% (0.6 dB)
Worst results	78.5% (1.05 dB)	80% (1.0 dB)
Average results	82.5% (0.85 dB)	83.7% (0.75 dB)
Number of measurements	11	13
Number of different ends	2	2

$\eta \cong 27$ percent for a 5-mil separation), which are in very good agreement with Bisbee's,[2] were observed more frequently than the bad ones.

In multifiber joints, it is unlikely that the axial separation of each pair of fibers will be as small as it was for the single pairs tested so far. However, one can think of enlarging the waist of the light beam in the fibers, by using a smaller normalized frequency[7]; the confocal length of the beam would then grow as the square of the beam waist. The effect of an axial separation upon the coupling efficiency would be smaller than that shown in Fig. 7.

3.2 *Tests at 9000 Å*

It was pointed out before that, while working with visible radiation, a misalignment or a gap between the fibers was revealed by a large amount of scattered light leaking from the joint. In a multifiber joint, this light will not identify the pair of fibers that form a leaky connection. Hence, it was necessary to check whether the very small number of mistakes in assembling the joints and the high average of their performances were independent of the information that the operator was provided by the scattered light.

A sequence of tests in the near infrared, at $\lambda \cong 9000$ Å (where $V \cong 1.55$), was then performed using a small-area GaAs LED.* The set-up differs from Fig. 5 only because the chopping of the signal is performed by an audio oscillator driving the LED. Launching spatially incoherent radiation into the fiber is much less critical than in the case of the laser; this results in a much smaller long-term drift of the reference level.

* The LED was built and provided by C. A. Burrus.[9]

Tests were performed on joints that made use of the grooved samples referred to in columns 2 and 3 of Table I. Quite repetitive results were obtained. They are summarized in Table II. Comparison with Table I shows a very slight deterioration of the best results (power coupling coefficients from 92–93 percent down to 87–87.5 percent) but even smaller changes of the averages (from 80–81 percent down to 78.5–80 percent) and almost no change in the lower ends of the range. Let us re-emphasize that the tested joints were not assembled while monitoring the transmitted power.

Comparison of both Tables I and II with previously published data on single-mode fiber joints[5] shows the desirability of the present sandwich technique. Best results given by the fusion technique[5] show power transmission efficiencies of ≈ 80 percent, at a normalized frequency $V \cong 2.0$; the average results given by the sandwich technique are better, both above and below that value of V.

The number of times when the attempts to assemble the joints were unsuccessful because of easily identified mistakes in the fiber position increased to three in a sequence of twenty-seven measurements, compared to one in twenty-five measurements at 6328 Å. This value is still low enough to insure that the technique is suitable for further developments in a multifiber system, where the risk of making such mistakes has to be negligible.

Some information on the importance of the index-matching oil has been collected, too: "dry" joints gave best power coupling efficiencies in the order of 50 percent. Comparison with available data[2] shows that the oil produces some other effect besides the elimination of end reflections. Quite likely, it compensates for irregularities of the end faces; also, it provides some alignment mechanism via surface tension. The last point is discussed further in the next section.

IV. EFFECTS OF DISCREPANCIES BETWEEN THE FIBER OUTER DIAMETERS

The usefulness of the sandwich technique would be limited if its performances were sensitive to discrepancies between the diameters of the two joined fibers, a situation that will occur in practice. The results reported in this section show that the sensitivity to this kind of imperfection is small enough to satisfy practical purposes.

A controlled difference, d, between the outer diameters of the fibers was introduced by etching one fiber with commercial hydrofluoric acid. First, a value $d \cong 10\ \mu m$ was chosen, because it would be sufficient to allow more than a complete offset of the two cores if the claddings were

TABLE III—POWER COUPLING EFFICIENCIES OF JOINTS BETWEEN FIBERS WITH A 10-μm DIFFERENCE IN CLADDING DIAMETERS. MEASUREMENTS PERFORMED AT 9000 Å.

Best result	86% (0.65 dB)
Worst result	82% (0.85 dB)
Average result	84.7% (0.7 dB)
Number of measurements	7
Number of different ends	2

aligned along one generatrix; besides which, 10 μm is 4 percent of the cladding diameter, which can be thought of as a realistic tolerance.

A new sequence of tests was performed at $\lambda \cong 9000$ Å, using the embossed sample referring to column 2 in Tables I and II. The results are summarized in Table III. Comparison with Table II shows that there is no appreciable deterioration of the joint performances. On the other hand, it was observed that the transmission was sometimes (not always) sensitive to small changes in the force applied by the vise; e.g., for one of the best joints assembled without monitoring the transmitted power ($\eta \cong 86$ percent), small changes in the tightening could cause a drop of the transmitted power to 82 percent or a raise to 89 percent (insertion loss ≈ 0.5 dB).

In all cases, releasing the vise slowly caused, first, a decrease in transmitted power; then a maximum, close to the figures quoted before, showed up; later, the signal decreased monotonically down to the noise level. The secondary maximum, which was very sensitive to vibrations and shocks, is believed to be entirely due to an alignment caused by the surface tension of the index-matching oil. The same phenomenon is believed to contribute to the excellent alignment under the strongly tightened vise, leading to the figures reported before.

Later, the difference between the cladding diameters was brought to a value $d \cong 30$ μm, i.e., about 12 percent of the outer diameter. The following behavior was observed:

(*i*) There was practically no coupling as long as the joints were not tightened very strongly. This was a remarkable difference with respect to the case of equal diameters, where the simple contact of the two faces, before squeezing the sandwich, could often produce a power transmission in the range 10 to 30 percent.

(*ii*) Several joints, assembled and very tightly squeezed without monitoring the transmitted power, had coupling efficiencies up to 40 to 50 percent and were not very sensitive to vibrations and shocks; however, the worst results ranged down to ≈ 10 percent (very seldom) or 20 percent (more frequently).

(*iii*) Repeated operations of tough tightening followed by partial releasing, while the transmitted power was monitored by a meter, led to coupling efficiencies in the range 80 to 84 percent. These joints were not tightly squeezed, and were very sensitive to vibrations and shocks, which could reduce the coupling all the way to 10 percent. Usually, though, the joints that had been disturbed, once abandoned to themselves, tended to restore spontaneously power coupling efficiencies up to 70 to 75 percent.

These observations and comparison with Bisbee's data[2] show that a remarkable alignment mechanism, due to the presence of the liquid, is still active for such a large difference between the cladding diameters, even if the performances are not any more suitable for practical applications.

V. CONCLUSION

Sandwich joints between single-mode fibers, aligned in embossed grooves, have been made and tested. This technique seems to suit very well the operation of splicing optical waveguides without using a microscope and without fusing their tips together. The average results obtained in this way–power coupling efficiencies ranging from 80 percent to almost 90 percent, i.e., insertion losses under 1 dB and down to 0.5 dB–compete successfully with the best results given by previous techniques.

The facts, that rather mediocre end surfaces of the fibers can be accepted and that cladding diameters can differ at least by a few percent without affecting the performances, induce confidence in the future use of the sandwich technique for splicing multifiber cables in the field. It seems that all the operations could be extended to fiber tapes, dealing with each of them as a whole. A fairly precise alignment of the fibers would be required as the result of the tape manufacturing process, but the final alignment should be provided by a set of precisely embossed grooves on a plate. The fibers ought to be forced into the grooves by means of carefully designed mechanical tools, but without microscopic observation and without dealing with them on an individual scale. The operations to be performed will depend on the ratio between the diameters of the fibers and their spacing in the tape, and on the precision of the preliminary alignment obtained in the manufacturing process. The absence of stringent requirements on the quality of the end faces, proved by the available results, suggests that a simultaneous and coplanar cut of all the fibers (for instance, scoring them by means of a razor blade while pulling along their axis) should be adequate.

VI. ACKNOWLEDGMENTS

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