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Lightguide Splice Loss—Effects of Launch Beam Numerical Aperture

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An experimental investigation is presented of the effects of launch beam numerical aperture (NA) on optical fiber lightguide splice loss measurements. With a short input fiber preceding the splice, the splice loss sensitivity to transverse offset is shown to be drastically reduced when the launch beam NA is significantly less than the fiber NA. With a launch NA greater than or equal to the fiber NA, the sensitivity to transverse offset is approximately equal to the steady-state (long input fiber) sensitivity for small offsets, but falls below the steady-state value for offsets greater than approximately 0.2 core radii. Displacing or tilting the launch beam relative to the fiber axis increases the measured loss. These observations emphasize the importance of strictly defining the measurement conditions when reporting splice loss results and the need for using a suitable mode filter if the steady-state splice loss is desired.

I. INTRODUCTION

The power loss in an optical fiber lightguide splice depends on a number of factors, both intrinsic and extrinsic. Intrinsic factors include mismatches of the core radius, r, the maximum relative index difference between core and cladding, Δ, and the power law profile parameter, α. Extrinsic loss mechanisms include angular misalignment as well as longitudinal and transverse offsets of the two fibers. The measured loss of a given splice also depends on the modal power distribution in the input fiber immediately preceding the splice which, in turn, depends on the nature of the source and the launching conditions used to excite the fiber and the length of fiber between the source and the splice.[1,2] A detailed knowledge of the exact measurement conditions is therefore necessary to adequately assess the significance of splice loss data.

One method of minimizing the influence of launching conditions on splice loss measurements is to use a long length of input fiber so that mode mixing produces a "steady-state" power distribution which is essentially independent of the launch distribution. It is often inconvenient or impossible, however, to use a long input fiber. Thus many splice loss measurements are made with a short input fiber, and some means is often employed to try to simulate a steady-state condition. On the other hand, there will certainly be cases in most fiber optic systems where short fiber lengths will precede a splice, and where a nonsteady state power distribution will be encountered.

For these reasons, a knowledge of the effects of launching conditions on splice loss is important. The present study was undertaken to quantitatively describe certain effects that are typically encountered in a beam optics splice loss measurement. The splice loss dependence on launch beam numerical aperture (NA) is covered in detail, and other launch-dependent phenomena are briefly discussed. Identical fibers are spliced to eliminate intrinsic losses, and the only splice parameter varied is the transverse offset, D, since this is usually the most important extrinsic parameter affecting splice loss. The experimental apparatus and procedures are described in the next section. The results are presented in Section III, and the final section contains a discussion and summary of these results.

II. APPARATUS AND PROCEDURES

The experimental arrangement is shown schematically in Fig. 1. A HeNe laser with a 10× beam expander was used as a source. A variable aperture wheel in conjunction with a 20×/0.38 NA microscope objective allowed the launch beam NA to be varied from 0.007 to 0.38 in 14 discrete steps. The launch end of the input fiber was held in a vacuum chuck and positioned with an x-y-z micropositioner. Care was taken in alignment to insure that the fiber axis was parallel to that of the launch beam.

Mode strippers were used on both the input and output fibers to eliminate cladding modes. The output fiber length in these measurements was ~1 m, while both long (500 to 1000 m) and short (~1 m) input fiber lengths were studied. The fiber ends were prepared by conventional score-and-break techniques, and the end quality was visually inspected using a microscope. Most of the data were taken with index-matching oil between the spliced fiber ends, but the results with dry splices were essentially the same.

Splice loss measurements were made using an automated transverse offset loss measurement set. The two fiber ends constituting the splice were held in right-angle vacuum chucks mounted on x-z and y-axis micropositioners. The vacuum chucks were carefully aligned to minimize any angular misalignment of the fiber axes. The longitudinal

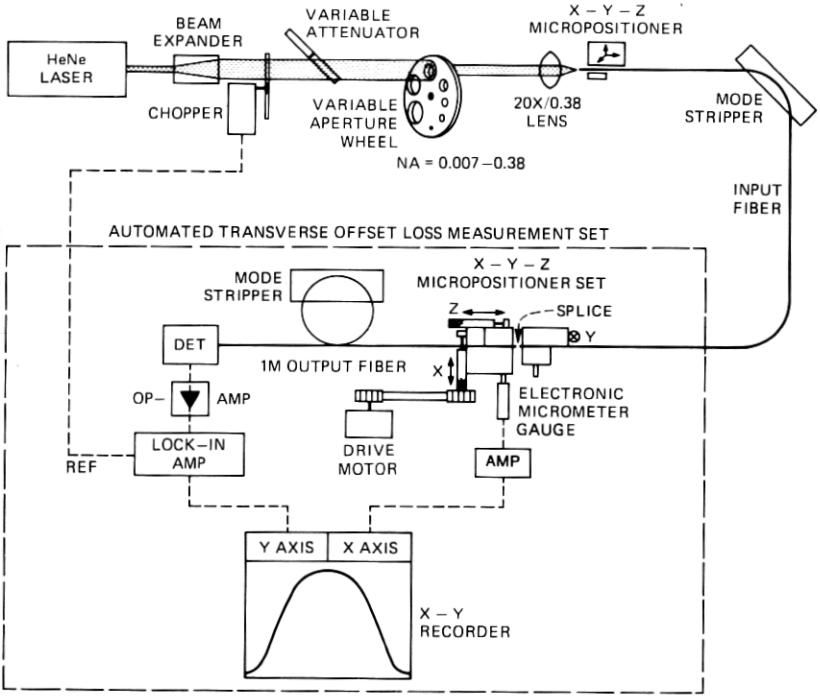

Fig. 1—Schematic of the measurement apparatus.

separation between the fibers was approximately 10 μm. The transverse (x-axis) micropositioner was mechanically driven by a variable speed motor, and the displacement was measured with an electronic micrometer gauge.

The output power was detected with a PIN photodiode followed by a lock-in amplifier. Analog outputs from the micrometer gauge and the lock-in amplifier were used to drive the x and y axes, respectively, of an x-y recorder. The y-axis gain was set to give a 100-percent reading when the splice transmission was maximized (zero transverse offset). Thus by driving the x-axis micropositioner, a plot of splice transmission (in percent) versus transverse offset was generated on the x-y recorder.

A typical recorder plot is shown in Fig. 2. The two overlapping traces were obtained by driving the micropositioner in opposite directions. The degree of coincidence of the two curves shows that both the mechanical and optical stability are quite good, and that backlash is not noticeable. Since each trace requires only about two minutes, the effects of any long-term laser drift are reduced.

The transmission curves as shown in Fig. 2 are not always perfectly symmetrical, i.e., the transmission for a given displacement in the $+x$ direction can differ by as much as several percent from the $-x$ value.

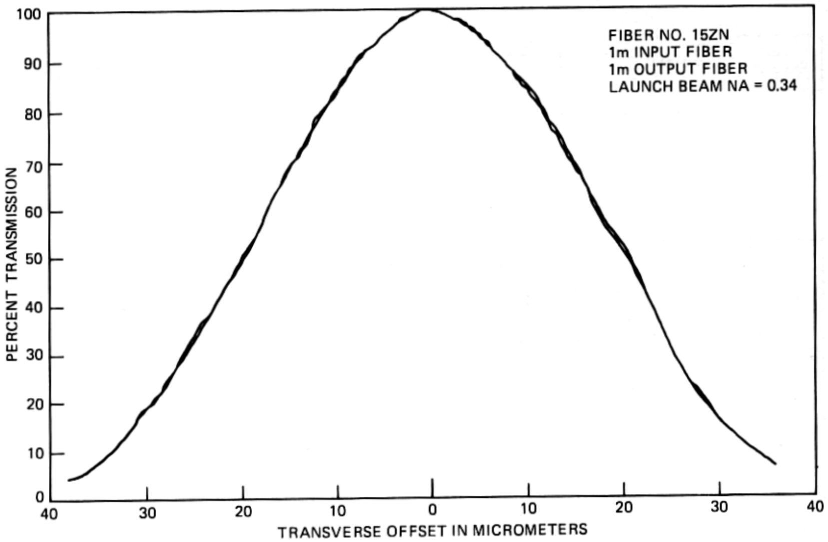

Fig. 2—Typical splice transmission versus transverse offset curve from the x-y plotter. The two overlapping traces result from traversing the core in opposite directions.

This phenomenon is related to the "speckle pattern" of the splice input fiber which is produced by interference of the coherent light propagating in the various fiber modes. Because of this speckle pattern, the power contained in a given region in the right fiber half can differ from the power in the corresponding region in the left half, and this can give rise to the observed nonsymmetry of the splice loss. Thus the raw transmission curves were folded about the $D = 0$ line, and an average curve was drawn through the resulting four curves (two traces each in the $+x$ and $-x$ directions).

III. RESULTS

Measurements were made on three different graded-index multimode fibers. The results are all quite similar, and thus only one will be discussed in detail. The parameters of this fiber are: $\alpha = 2.2$, $\Delta = 0.98$ percent (NA $= 0.21$), and core radius $r = 26.9\ \mu$m.

A set of splice transmission curves for several different launch beam NAs is shown in Fig. 3. The dotted curve is for the case of a long (900 m) input fiber, where the splice loss is insensitive to launch NA; the other curves are for a short (1-m) input fiber. These data were all taken with the launch beam centered on the fiber core (the effect of noncentered launching is discussed subsequently). The "error bars" in the legend indicate typical values of the *maximum* difference among the four raw traces, including both measurement system noise and any nonsymmetry.

Several conclusions may be drawn from Fig. 3. First, for offsets of less than about 1.1 core radii, the splice loss sensitivity to transverse offset with a short input fiber is significantly reduced when using a launch NA which is much less than the fiber NA. A small launch NA excites primarily the low-order fiber modes which propagate near the center of the fiber core, and these modes are least affected by small splice offsets. For offsets much greater than one core radius, however, the situation is reversed. Also, increasing the launch NA beyond the fiber NA is shown to have very little effect on the splice loss.

The second important observation is that, over most of the range of

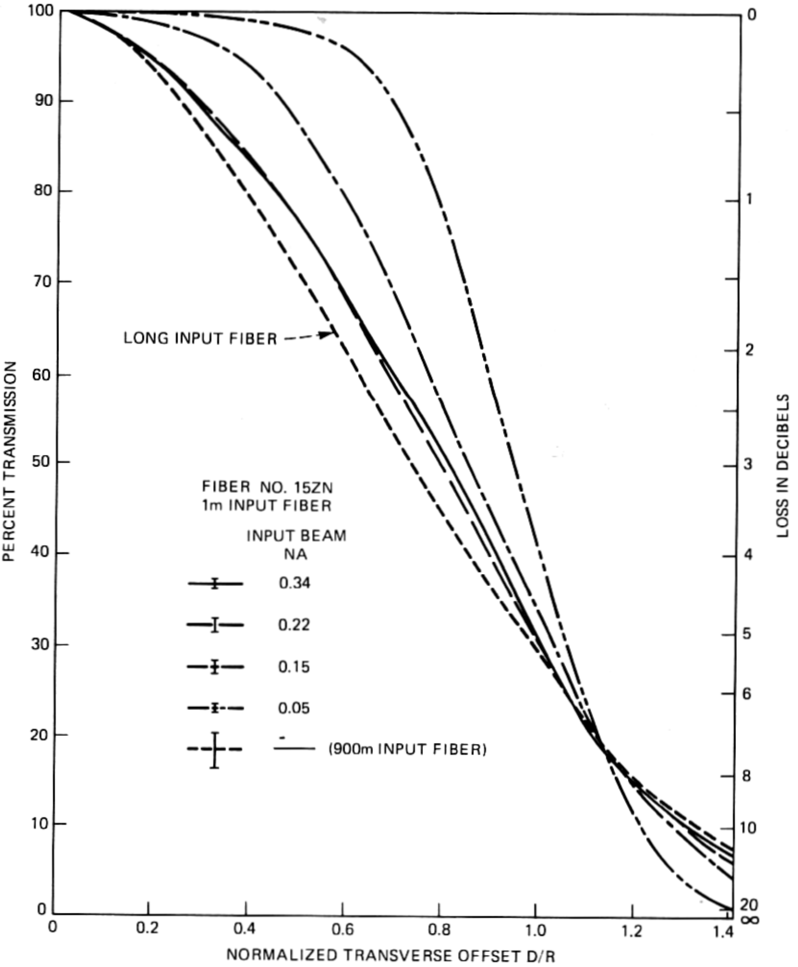

Fig. 3—Splice transmission versus transverse offset, normalized to the fiber core radius, for various input conditions. The dotted curve is for a 900-m input fiber, and the other curves are for a 1-m input fiber with different launch beam NAS.

interest, the splice loss measured with a long input fiber is greater than that measured at any NA with a short input fiber. This result suggests that by launching on-axis with a Gaussian beam we are only exciting meridional fiber modes, while the steady-state power distribution in the long input fiber contains additional higher order skew modes which can significantly affect the splice loss.

In an attempt to launch more skew modes into a short input fiber, measurements were made with the launch beam displaced or tilted with respect to the fiber axis. Indeed, either of these was found to increase the measured splice loss. The magnitude of this effect depends upon many factors, but generally a launch beam displacement of ~0.5 core radii or an angular misalignment of ~3 degrees results in a 10 to 30 percent increase in splice loss, depending on the offset.

For fibers with an index dip, the maximum launching efficiency typically occurs when the beam is displaced slightly (0.1 to 0.2 core radii) from the fiber core center. Thus, short input fiber loss data taken with peaked power launching conditions generally show a slightly greater sensitivity to transverse offset than data taken with a centered launch beam. For the three fibers studied, however, this effect was smaller than the observed difference between the short and long input fiber splice loss.

IV. SUMMARY AND CONCLUSIONS

An investigation of the effects of launch beam NA on the transverse offset splice loss has been described. It was shown that the splice loss sensitivity to transverse offset is significantly reduced when using a small launch NA with a short input fiber. When the launch NA is equal to or greater than the fiber NA, the short input splice loss is approximately equal to the steady-state loss for small offsets, but falls below the steady-state value for offsets in the 0.2–1.1 core radii range.

Previous work by Cherin and Rich[2] indicated that the steady-state splice loss could be approximated with a short input fiber by using peaked power launching conditions with a launch NA slightly smaller than the fiber NA. Our results imply that this is only true for small offsets. We do find, however, that the measured short length loss is increased by displacing or tilting the launch beam relative to the fiber axis, since this excites higher order skew modes which are present in the steady-state distribution but are not excited by launching on-axis.

The observed sensitivity of splice loss to practically any kind of change in launching conditions emphasizes the importance of strictly defining the measurement conditions when reporting any splice loss results. If the steady-state splice loss is desired, a long length of fiber or some other suitable mode filter is recommended. The loss of any splice between the mode filter and the measured splice must be kept small, however, in order not to significantly disturb the steady-state power distribution.[3]

V. ACKNOWLEDGMENTS

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