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The Effect of Optical Fiber Core and Cladding Diameter on the Loss Added by Packaging and Thermal Cycling

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We conducted an experimental investigation of the effect of fiber cladding and core diameters on the loss added by packaging and thermal cycling. The results confirm the general trends predicted by theory and indicate that fibers with 125-μm claddings and 50-μm cores should have about three times less microbending loss than 110-μm/55-μm fibers. These results contributed to the adoption of the 125-μm/50-μm dimensions for the FT3 metropolitan trunk lightwave system.

I. INTRODUCTION

The Bell System's Atlanta fiber system experiment[1] in 1976 and Chicago lightwave communications project[2,3] in 1977 to 1979 both used optical fibers with 110-μm cladding diameter and 55-μm core diameter. In 1979, an experimental investigation was conducted into the effect of core and cladding diameter on the loss added by packaging and thermal cycling. The results of that study are reported here. These results contributed to the adoption of 125-μm/50-μm fiber dimensions for the Bell system's new FT3 metropolitan trunk lightwave system.[4,5]

The conflicting requirements on the core diameter (a) and the cladding diameter (d) are summarized in Table I.

This study is directed at items 1 and 2 of Table I. Items 3 (at least for lasers) and 4 are somewhat more difficult to quantify, and will not be addressed here.

Table I—Requirements on dimensions

Design Consideration	Dictates that a be	Dictates that d be
1. Splice Loss	large	—
2. Microbending Loss	small	large
3. Source Coupling Efficiency	large	—
4. Cost	small	small

II. THEORY

2.1 Splice loss

When offset dominates over fiber parameter mismatch, the splice loss γ_s (based on Fig. 9 of Reference 6) obeys to first order

$$\gamma_s \propto (c/a)^{1.5}, \tag{1}$$

where c is the transverse offset, a is the core diameter, and $c/a \lesssim 0.4$. Equation (1) gives

$$\gamma_s(a)/\gamma_s(55\ \mu\text{m}) = [(55)/a]^{1.5}, \tag{2}$$

where a is in μm. Equation (2) is referred to as the predicted splice loss factor in Table II.

2.2 Microbending loss

Using Olshansky's[7] model for the microbending loss γ_m resulting from fiber packaging,

$$\gamma_m \propto a^4/d^6, \tag{3}$$

where a is the core diameter and d is the cladding diameter. From this, the predicted microbending loss factor in Table II is calculated,

Table II—Summary of ribbon performance

Clad Dia. (μm)	Core Dia. (μm)	Clad / Core	Ribbon Number	Mean Ribbon Minus Fiber Loss (dB/km) 1 hr	Mean Ribbon Minus Fiber Loss (dB/km) 100 hrs	Measured Ribboning Loss Factor* (Normalized to 110/55) 1 hr	Measured Ribboning Loss Factor* (Normalized to 110/55) 100 hrs	Measured −43°F Loss Factor* (normalized) (from Table III)	Predicted Microbending Loss Factor Eq. (4)	Predicted Splice Loss Factor Eq. (2)
110	55	2.0	84	2.63	2.24	1.00	1.00	1.00	1.00	1.00
110	44	2.5	81	0.79	0.70	0.30	0.31	0.30	0.41	1.40
110	37	3.0	88	1.52	0.95	0.58	0.42	—	0.21	1.81
90	36	2.5	89	1.77	1.60	0.67	0.71	—	0.61	1.89
90	30	3.0	87	1.56	1.96	0.59	0.88	—	0.30	2.48
125	50	2.5	82	0.95	1.04	0.36	0.46	0.18	0.32	1.15
125	42	3.0	90	0.60	0.52	0.23	0.23	—	0.16	1.50

* Normalized to the 110/55 case (Ribbon 84).

$$\gamma_m(a, d)/\gamma_m(55,110) = (a/55)^4/(d/110)^6, \quad (4)$$

where a and d are in μm.

Calculations indicate that based on packaging and splicing losses, the repeater spacing for the Bell system's FT3 laser system would be optimized for clad/core diameter ratios (d/a) in the range of 2.5 to 3.0. These calculations closely parallel those of Murata et al.,[8] who conclude that the optimum d/a for their laser-based system is 2.5, and for a light emitting diode (LED)-based system, between 1.8 and 2.0.

III. FIBER PREPARATION

To develop confidence in these paper studies, preforms were prepared having d/a ratios of 2.0, 2.5, and 3.0. Standard modified chemical vapor deposition (MCVD) processing techniques[9] were used to fabricate the germanium borosilicate 0.23 N.A. graded-index preforms. After depositing three barrier layers of fused silica, the $SiCl_4$, BCl_3, and additional O_2 levels were held constant while linearly varying the $GeCl_4$ concentration during deposition of the core.

For the 2.0 clad/core ratio preform fabrication, 50 passes were used with slight adjustments in the number of passes to compensate for tube cross-sectional area variations. The number of passes had to be reduced to ~28 for fabrication of a 2.5 clad/core preform at equivalent traverse speeds and tube sizes. This resulted in an equivalent layer thickness (μm/pass) in the resultant preform. For the 3.0 clad/core preforms, the traverse speed was slightly increased to maintain a reasonable number of grading passes without a marked reduction in deposited layer thickness. The effect of layer thickness on loss is not well understood.

After deposition each tube was collapsed in similar fashion to form a preform. A reverse collapse procedure applying internal pressure was used.

Approximately 1 km of optical fiber was drawn from each preform to 110-μm cladding diameter and coated with silicone. Figure 1 shows the distribution of 820-nm losses in these fibers. The remaining portions of the preforms were drawn to 90-, 110-, and 125-μm cladding diameters and coated with a polyurethane acrylate. The loss trends with this coating were similar to Fig. 1 and suggest that fibers with higher clad/core ratios are less sensitive to process-induced loss. For all values of d, the nominal coating outer diameter was 229 μm.

IV. PACKAGING LOSS

For each of the seven combinations of fiber dimensions shown in Table II, one 12-fiber adhesive sandwich ribbon,[10] approximately

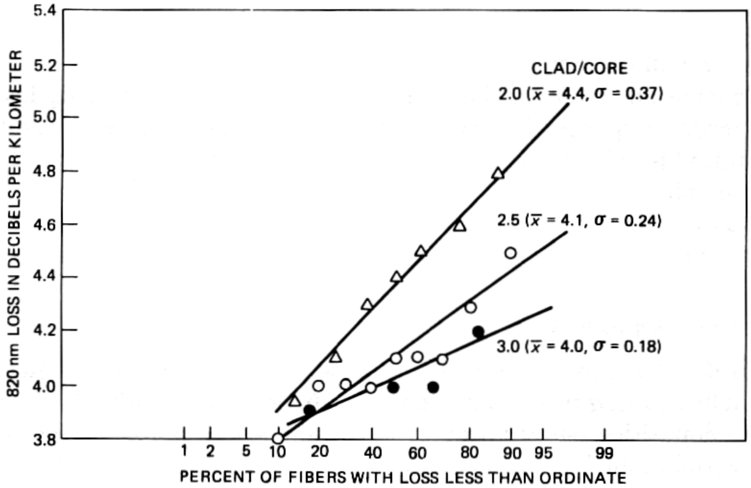

Fig. 1—Impact of fiber dimensions on loss. Distribution of losses in unpackaged silicone coated fibers with 110-μm cladding diameter.

1-km-long, was made. Since the silicone coating was not compatible with this process, only the acrylate coating was used in the packaging loss experiment. Before making the ribbons, spectral loss was measured[11] with the fibers laid in a 58-cm-diameter container to eliminate added loss caused by reel winding. For these measurements, the fiber core (regardless of diameter) was overfilled, and the leaky and higher-order modes were eliminated by winding five turns of the fiber around a 13-mm-diameter mandrel. For each preform used, the core diameter and refractive index profile were checked.

The 633-nm loss of each fiber in each ribbon was measured about one hour after making the ribbon and again about 100 hours later. (Some change occurs over this time because of relaxation in the ribbon structure.) The microbending loss at 633 nm, because of the ribbon making, is shown in Table II for each ribbon as "mean ribbon minus fiber loss." These values are then normalized to the 110/55 clad/core case under the heading "Measured Ribboning Loss Factor."

V. THERMAL CYCLING

After determining the added loss in the ribbons, three of the seven ribbons were laid in 58-cm-diameter containers and placed in an environmental chamber. The mean 633-nm loss for the 12 fibers in each ribbon was determined at 75°F and entered as "baseline" in Table III. The remaining values in Table III are changes from this baseline loss after the temperature–time exposure indicated. The changes at the final low-temperature exposure (−43°F) are then nor-

Table III—633 nm loss change with temperature (dB/km)

Temperature (°F)	Exposure Time (h)	Clad/Core → Clad Dia. →	2/1 110 μm Ribbon 84	2.5/1 110 μm Ribbon 81	2.5/1 125 μm Ribbon 82
75		Baseline	12.33 ± 0.03	12.31 ± 0.10	11.78 ± 0.06
−45	48		+1.09	−0.07	−0.09
−15	48		+0.48	−0.09	−0.20
20	48		−0.03	−0.14	−0.12
75	48		−0.10	0.00	−0.05
190	816		0	+0.59	+0.57
75	48		+0.02	+0.30	+0.23
−45	48		+1.04	+0.21	+0.06
−9	48		+0.45	+0.12	0
15	48		+0.11	+0.11	+0.19
75	48		−0.04	+0.26	+0.24
190	1104		−0.01	+0.61	+0.61
75	48		+0.07	+0.31	+0.28
−40	48		+1.33	+0.35	+0.19
−15	48		+0.68	+0.29	+0.13
75	72		−0.18	+0.31	+0.26
190	2376		+0.07	+0.72	+0.76
75	48		+0.33	+0.59	+0.42
−43	48		+2.10	+0.64	+0.38
−15	48		+1.29	+0.42	+0.24
+15	48		+0.52	+0.36	+0.27
75	48		+0.03	+0.38	+0.36

malized to the 110/55 ribbon's change at −43°F and recorded in Table II as the "measured −43°F loss factor."

VI. DISCUSSION AND CONCLUSIONS

The microbending loss factor defined by eq. (4) and entered in the second column from the right in Table II is supposed to indicate the relative expected susceptibility of the various fibers to microbending loss. Two occasions when microbending loss appears are (*i*) in the packaging of the fibers into a ribbon, and (*ii*) the temperature cycling of the ribbon. The measured susceptibility of the various fibers in those two instances is indicated by the measured ribboning loss factor and the measured −43°F loss factor, respectively, in Table II. In general, these values follow the trends predicted by eq. (4) as a and d vary. Except for the cases of $d/a = 3.0$, where the ribboning loss was consistently larger than predicted, numerical agreement between theory and experiment is good. Although the coatings and ribbons were nominally the same throughout, some randomness in coating roughness, modulus, and ribbon structure undoubtedly weakened the correlation between theory and experiment. Nevertheless, the general trends of loss versus cladding and core diameters are confirmed. Based on these results, the 125/50 fiber is expected to provide about a factor of three, less microbending loss, than the previously used 110/55 fiber. From the last column in Table II, this change in dimensions should sacrifice only about 15 percent in splice loss. This is the lowest splice loss factor of any of the alternatives to 110/55 investigated here. Thus, the 125/50 combination appears to be a good compromise between microbending loss and splice loss. Since there is more glass per unit length in the 125-μm fiber, its cost will be higher. Where cost is critical, other dimensions will probably be preferred. Thus, it is important that the adoption of the 125/50 dimensions for FT3 not preclude the eventual use of other dimensions as dictated by future needs.

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REFERENCES

1. For articles on the Atlanta system experiment, see B.S.T.J., *57,* No. 6 (July–August 1978), Part 1.
2. M. I. Schwartz, W. A. Reenstra, J. H. Mullins, and J. S. Cook, "The Chicago Lightwave Communications Project," B.S.T.J., *57,* No. 6 (July–August 1978), pp. 1881–8.
3. T. C. Cannon, D. L. Pope, and D. D. Sell, "Installation and Performance of the Chicago Lightwave Transmission System," IEEE Trans. Commun., *COM-26,* No. 7 (July 1978), pp. 1056–60.
4. I. Jacobs, "Lightwave Communications Begins Regular Service," Bell Labs Record, *57,* No. 11 (December 1979), pp. 298–304.
5. I. Jacobs, "Lightwave Communications—Yesterday, Today, and Tomorrow," Bell Labs Record, *58,* No. 1 (January 1980), pp. 2–10.
6. C. M. Miller and S. C. Mettler, "A Loss Model for Parabolic-Profile Fiber Splices," B.S.T.J., *57,* No. 9 (November 1978), pp. 3167–80.
7. R. Olshansky, "Distortion Losses in Cabled Optical Fibers," Appl. Opt., *14,* No. 1 (January 1975), pp. 20–1.
8. H. Murata, S. Inao, Y. Matsuda, and T. Kuroha, "Optimum Design for Optical Fiber Used in Optical Cable System," Proceedings of Fourth European Conference on Optical Communication, Genoa, Italy (September 12–15, 1978), pp. 242–8.
9. F. V. DiMarcello and J. C. Williams, "Reproducibility of Optical Fibers Prepared by a Modified Chemical Vapor Deposition Process," B.S.T.J., *57,* No. 6 (July–August 1978), pp. 1723–34.
10. M. J. Saunders and W. L. Parham, "Adhesive Sandwich Optical Fiber Ribbons," B.S.T.J., *56,* No. 6 (July–August 1977), pp. 1013–4.
11. L. Wilson and M. J. Buckler, "Automated Spectral Loss Measurement of Optical Fibers," Optics and Laser Technology, *10,* No. 4 (August 1978), pp. 197–9.