Developments in Single-Mode Fiber Design, Materials, and Performance at Bell Laboratories

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Abstract—Some aspects of single-mode fiber research and development at Bell Laboratories are presented. The most recent evolution in single-mode fiber design and fabrication technology has resulted in a fiber in which mode size and zero dispersion wavelength can be independently chosen at a fixed cutoff wavelength.

Introduction

PROGRESS in single-mode fiber design and fabrication has been made at an increasingly high rate during the last two years. Whereas early work in single-mode fibers was directed towards understanding the fundamentals of waveguiding properties, more recent work has been directed toward overcoming a number of specific problems that affect fiber performance in anticipated single-mode lightwave systems.

The work of many other investigators in fabricating single-mode fibers and exploring their properties is recognized. Noteworthy is the research conducted at a number of Japanese laboratories as reviewed by Murata and Inagaki [1], at the British Telecom Research Laboratories as summarized by Ainslie *et al.* [2] and Midwinter [3], and at Standard Telecommunication Laboratories as reported by Irven *et al.* [4]. The purpose of this paper is to report some of the recent work which has been done on single-mode fibers at Bell Laboratories.

The first single-mode fibers made at Bell Laboratories used the $B_2O_3:SiO_2$ materials system [5]. Study of these fibers was largely confined to the 0.7-1.1 μm spectral region. One important finding of this work was that a thick low-loss deposited cladding is required due to the sizable fraction of the mode power in the cladding region. Processing difficulties associated with fibers having a pure SiO_2 core were overcome by lightly doping the core with B_2O_3 to reduce the processing temperature [6]. Single polarization fibers were also fabricated using this materials system [7], [8].

In 1979, the proposal for a transatlantic undersea lightguide cable [9] focused research attention on single-mode fibers that would be suitable for long haul, high data rate systems use. Interest shifted from the 0.7-1.1 μm region to the 1.2-1.6 μm region because in this wavelength range the material dispersion can be tailored to cancel the waveguide dispersion, resulting in very high bandwidth. Several very challenging technical problems immediately became apparent and single-mode fiber design became dominated by the need to address these problems. The requirements were

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1) low loss fibers (less than 1 dB/km) near 1.3 μm to allow 30-50 km repeater spacings;

2) low curvature induced loss to allow use of the fibers in a variety of cable structures;

3) low dispersion near 1.3 μm to allow data rates of 274 Mbits/s and above; and

4) high fiber strength to allow cable manufacture as well as recovery and repair operations, requiring the fiber to pass proof-test levels in the range 150-250 ksi in long lengths.

In the following sections we will discuss three single-mode fiber designs that attempted to address these problems. Only the Type VI (which is chronologically the latest) design is able to meet all the performance requirements simultaneously.

In the text of this paper, we refer to the various designs as Type I, Type II, etc. This is our internal nomenclature and is used here instead of repetitious many-worded descriptions. Fig. 1 depicts what each type designation represents. All the fibers described in Fig. 1 and discussed in this paper are made by the modified chemical vapor deposition (MCVD) process [10].

The Type V Design

The need to operate near 1.3 μm required abandoning the B_2O_3-SiO_2 system because of unacceptably high absorption due to the tail of the B-O stretching vibration. The first single-mode fiber designed for use at wavelengths longer than 1 μm used a GeO_2-SiO_2 core composition surrounded by a pure silica deposited cladding. The high processing temperature of the cladding required the use of a pressurizing device to prevent premature substrate tube collapse [11]. This design, designated Type III, was soon superseded by the Type V design [12]-[14].

The Type V single-mode fiber structure consists of a germania doped silica core surrounded by a lightly phosphorous oxide doped silica cladding. The phosphorus oxide doping of the cladding is done solely to reduce the processing temperature below that required for a pure silica cladding. Since phosphorus oxide raises the refractive index of silica slightly, the cladding of the Type V fiber has a slightly positive Δ', so that under some circumstances it can act as a secondary waveguide. For this reason the doping level must be kept as low as possible. In the case of the core, in order to obtain high bandwidths, the germania doping level must be kept low enough to provide zero total dispersion at the operating wavelength. This may render the fiber susceptible to curvature induced loss because of poor mode confinement. In addition, the operating wavelength lies in a valley between the 1.39 μm OH absorption peak and the combination band at 1.25 μm. Thus, any sub-

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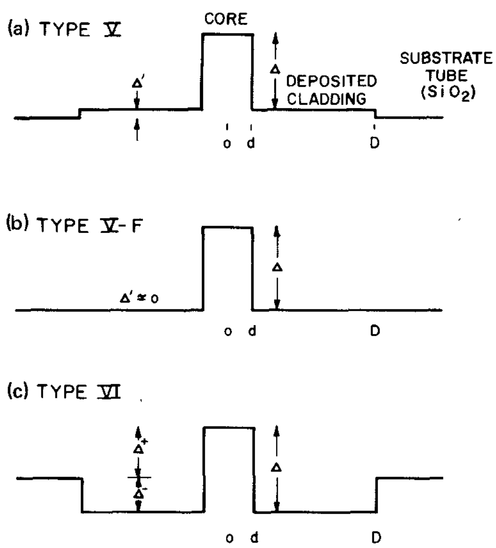

Fig. 1. Idealized refractive index profiles of (a) Type V, (b) Type V-F, and (c) Type VI single-mode fibers.

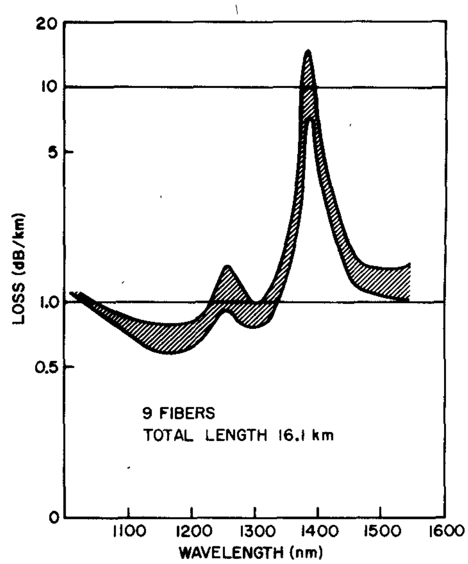

Fig. 2. Envelope of loss curves for 9 fibers of the Type V structure having $\Delta \sim 0.22$ percent, $\Delta' \sim 0.02$ percent, 10 μm core diameter, and ~ 110 μm OD.

stantial amount of hydroxyl contamination in the structure of the fiber may increase the loss at 1.3 μm.

Type V Large Core Low Δ Fibers

The first attempt to fabricate fairly large quantities of fiber with uniform properties was undertaken in support of an exploratory undersea cable. The cable was to be 1 km long and to contain 12 fibers. A total of 16 km of fiber was fabricated for this experiment. The design which evolved was very similar to that developed by Miya and his co-workers [13]. The core of the fiber was germania doped silica with a Δ value of about 0.22 percent, and the cladding was composed of silica lightly doped with phosphorus oxide. The Δ' value of the cladding was about 0.02 percent. The fibers were fabricated by conventional MCVD [10] in 13.5 × 16 mm Hereaus TO-8 WG substrate tubes. The initial goal was that the loss at 1.3 μm should be less than 1 dB/km. The envelope of the loss spectra of the fibers prepared for this experiment is shown in Fig. 2. As can be seen, although the 1 dB/km goal was met, the fibers show an increase in loss at long wavelengths. Subsequent experiments have shown this loss at long wavelengths to be a curvature-induced phenomenon.

The problem with low Δ designs is related to the poor mode confinement that results from the dependence of the modal spot size ω_0 on λ and Δ; $\omega_0 \sim \lambda/\sqrt{\Delta}$. This causes an enhanced sensitivity of the fiber to curvature induced loss at long wavelengths. Typically, we have found that in low Δ fiber designs ($\Delta \leqslant 0.3$ percent) the excess, or curvature induced loss varies as ω_0^7! Thus a modest increase in Δ results in a very dramatic reduction in curvature induced loss. This can be confirmed by a very simple experiment. The transmitted power through a short length of fiber (~3 m) is monitored as the radius of a single circular loop in the fiber is decreased. The radius that corresponds to a 3 dB drop in transmitted power compared to the unbent fiber condition is a good measure of the mode confinement and thus of the curvature induced loss sensitivity of the fiber. The 3 dB loop radius for these low Δ fibers increased from 6 mm near $\lambda = 1.3$ μm to about 36 mm at $\lambda =$ 1.54 μm, indicating a large sensitivity of this fiber to bend-induced loss. The 3 dB loop radius measurement represents a simple and novel method of evaluating curvature induced losses.

The loss spectra of similar fibers reported earlier by Miya did not show this long wavelength loss phenomenon. There are two possible reasons for this. The first is that Miya's fibers had an outside diameter of 125 μm as compared to the 110 μm diameter of our fibers. This larger diameter structure is expected to be more robust and thus more resistant to externally induced curvature. The second factor was that Miya's fibers were coated with a thick coating of soft silicone resin, which would cushion them from curvature producing irregularities impressed upon the fiber from the outside, whereas the fibers of Fig. 2 had a thin, hard coating of UV-cured epoxy-acrylate. From the manufacturing point of view, the disadvantage of using a large outside diameter is that the fiber length yield for a given preform is reduced in proportion to the square of the diameter of the fiber, so that in using a diameter of 125 μm one would produce only three quarters of the length of fiber which would be available if the same preform were drawn to an outside diameter of 110 μm. In addition, the use of a soft cushioning silicone resin coating makes proof-testing of the fiber difficult at the 2 percent strain levels required.

Scale-Up

Another problem that was noted during the preparation of the fibers for the last mentioned experiment was the low overall production rate. Initially, the preforms provided about 3 km of fiber at a rate of about 0.5 km/h of time spent on the glass-working lathe. The process was scaled up by depositing the glass materials by MCVD at higher rates and employing larger substrate tubes; the same approach that has been successful in improving the processing rate of multimode preforms prepared by MCVD [15].

The scale-up was accomplished by employing standard 19 × 25 mm substrate tubes. In addition, the deposition rate during the MCVD process was increased from about 0.15 to 0.5 g of glass per minute. A third option employed the fabrication of a preform followed by subsequent shrinkage of a second tube over the preform (overcladding) before the fiber was drawn [16]. This approach provided preforms that yielded 40 km of fiber at an effective rate of 3.5 km/h [17].

Type V Small Core High Δ Fibers

As a result of an extensive study of fibers with core diameters ranging from 6-10 μm and Δ values ranging from 0.6-0.2 percent an alternative design having improved resistance to curvature induced loss was obtained.

Large preforms made at high rates were fabricated and drawn into fiber with core diameter 7.5 μm and a Δ of 0.5 percent. Excellent loss spectra were obtained, but there was a variability of fiber properties from one preform to the next, and also along the length of an individual preform. This was again partly due to the presence of the slightly positive Δ' cladding region which appeared to be acting as a secondary waveguide.

A 20 km continuous length of fiber was drawn in order to investigate the bandwidth. The results indicated a zero dispersion wavelength λ_0 of 1.35 μm and a 1.3 μm bandwidth between 20 and 25 GHz km, which might be adequate for a 274 Mbit/s operation, but would not be adequate for rates higher than that [18]. This 20 km length of fiber was operated in an experimental system at 274 Mbits/s error free [19].

Bending tests carried out on this type of fiber confirmed that it was very resistant to curvature induced losses and was therefore suitable for further study in cabling experiments.

Type V-F Small Core, High Δ Fibers

In order to eliminate the secondary waveguide of the Type V design the refractive index of the cladding was reduced so that it was essentially equal to the refractive index of the substrate tube. We have already mentioned that phosphorus oxide doping of the cladding is necessary in order to provide a reasonable processing temperature. However, in most cases pressurizing devices are used even with phosphorus oxide doping in order to reduce or prevent tube shrinkage during the deposition phase of the MCVD process. In our work we gradually increased the phosphorus oxide doping level until the processing temperature had been reduced to such an extent that tube shrinkage during the deposition was negligible without pressurization. We then introduced fluorine into the structure via Freon 12®. The incorporation of fluorine has very little effect on processing temperature but results in a large reduction in the refractive index of the structure. Therefore, sufficient fluorine was introduced into the deposit to balance the positive contribution to the refractive index of the phosphorus oxide doping while still maintaining a reasonable processing temperature. In fact, in most cases, the cladding was slightly overdoped with fluorine so that the refractive index of the cladding was about 0.02 percent less than that of the fused silica substrate tube. Schott and Abbe [20] discovered the effect of fluorine in reducing the refractive index of silicate glasses in the late nineteenth century, and the use of fluorine doping in optical fiber claddings has been reported previously [21]-[24].

Over 100 km of fiber were prepared to this design (core diameter 7.5 μm; OD = 110 μm; Δ = 0.5 percent) using seven preforms [17]. Two of these preforms were overclad structures which were capable of yielding about 40 km of fiber each. The other five were regular preforms which would yield between 15 and 20 km of fiber.

The success of this design with a slightly negative Δ' is apparent from the results which are summarized in Table I. The average loss at 1.3 μm for the total 108.5 km of fiber was 0.644 dB/km with a standard deviation of 0.074. This represents a 100 percent yield from the preparation of the preforms. Measurements of the dispersion in the fiber again indicated a λ_0 of 1.35 μm and that it would be suitable for 274 Mbit/s transmission but would not be suitable for data rates very much higher than that, or for repeater spans greater than about 25 km.

The curvature induced loss sensitivity was measured via the 3 dB loop test described above. An increase in the loop radius from 3.3 mm near 1.3 μm to only 3.6 mm at 1.55 μm indicated excellent mode confinement.

Type V-F Larger Core, Moderate Δ Fibers

The reason for the limited 1.3 μm bandwidth measured on the fibers discussed above is that the high doping level of germanium in the core results in the material dispersion cancelling the waveguide dispersion at a wavelength about 1.35 μm. At this wavelength the bandwidth of the fiber would be enormous [18], but falls off so rapidly as a function of wavelength as one moves from 1.35 towards 1.3 μm that the bandwidth values at 1.3 μm are not adequate for the high data rates and long repeater spacings allowed by the low fiber loss. The solution to this problem would seem to be to reduce the germanium doping level in the core such that the reduced materials dispersion contribution cancels the waveguide dispersion at a wavelength close to 1.3 μm. In order to keep the cutoff wavelength fixed in the vicinity of 1.2 μm one has to increase the core size: a core size of about 9 μm together with a Δ value of 0.35 percent was chosen, with Δ' still maintained at or slightly below zero.

A total of 45 km of fiber was fabricated for this experiment. The fiber was drawn in 5 km lengths from 5 preforms. Table II shows a summary of the optical properties of the nine 5 km lengths of fiber. The average loss at 1.30 μm was 0.54 dB/km with a standard deviation of 0.11. The bend induced loss sensitivity of this fiber was not as good as the small core high Δ fibers, but was much better than the earlier 10 μm core design.

The wavelength of zero total dispersion of these fibers was very close to 1.31 μm and consequently the bandwidth at that wavelength was very high. Table II summarizes the dispersion data for these fibers as obtained from group delay versus wavelength measurements. These fibers exhibit sufficiently low dispersion to be usable at 274 Mbits/s over a 35 km span length with negligible dispersion penalty for a source with less than a 2 nm rms spectral width. If a 1 dB dispersion penalty is acceptable, then operation at greater than 400 Mbits/s over 35 km spans is possible. Successful operation at 274 Mbits/s over a 35 km length with a 6 dB margin has been demonstrated [25]. The envelope of loss spectra of the 7 fibers which were fusion spliced together for this experiment is shown in Fig. 3.

TABLE I
SUMMARY OF THE PROPERTIES OF TYPE V-F FIBERS WITH 7.5 μm CORE DIAMETER AND Δ = 0.5 PERCENT

PREFORM No.	CUTOFF WAVELENGTH μm	LOSS AT 1.30 μm dB/km	LOSS AT 1.60 μm dB/km
226*	1.273 ± .023	.676 ± .062	.420 ± .056
304*	1.237 ± .029	.663 ± .049	.340 ± .036
309	1.267 ± .036	.728 ± .087	.368 ± .070
313	1.232 ± .044	.600 ± .036	.337 ± .049
320	1.200 ± .017	.593 ± .025	.308 ± .017
325	1.219 ± .026	.538 ± .038	.283 ± .013
327	1.210 ± .017	.627 ± .012	.327 ± .050
MEANS	1.239 ± .037	.644 ± .074	.348 ± .060

* OVERCLAD PREFORM

STANDARD DEVIATION IS INDICATED

TOTAL FIBER LENGTH = 108.5 km

TABLE II
SUMMARY OF THE OPTICAL PROPERTIES OF TYPE V-F FIBERS WITH 9 μm CORE DIAMETER AND Δ = 0.35 PERCENT

FIBER NO.	LENGTH (km)	CUTOFF WAVELENGTH (μm)	LOSS AT 1.30 μm (dB/km)	LOSS AT 1.60 μm (dB/km)	ZERO DISPERSION WAVELENGTH (μm)	OUTER DIAMETER (μm)
511-2	5.0	1.196	0.47	0.25	1.318	116
511-3	5.0	1.178	0.44	0.21	1.321	120
513-1	5.0	1.080	0.46	0.32	1.312	110
513-2	5.0	1.101	0.75	0.64	1.340	108
513-3	5.0	1.266	0.58	0.26	---	107
514-1	5.0	1.094	0.48	0.29	1.307	110
514-2	5.0	1.306	0.55	0.36	1.308	108
514-3	5.0	1.127	0.45	0.26	1.307	113
514-4	5.0	1.170	0.68	0.81	1.307	110
	45 km	1.170	0.54	0.38	1.315	111
		±0.078	±0.11	±0.21	±.011	±4

STANDARD DEVIATION IS INDICATED

TYPE VI FIBER DESIGN

From the discussion so far it is clear that a tradeoff between core diameter, Δ, and 1.3 μm dispersion is required in Type V designs. What is clearly required is a fiber design that avoids these tradeoffs!

Specifically, a fiber design is required that allows λ_0 to be positioned near 1.3 μm while at the same time allowing a core diameter and Δ selection that provides tight mode confinement and thus superior cabling properties. The Type VI design accomplishes this through manipulation of the materials dispersion of the core and cladding glass compositions [26]-[28]. By reducing the GeO_2 doping level in the core so that the core-to-substrate index difference corresponds to a Δ^+ of ~0.3 percent while heavily doping the phosphosilicate cladding with fluorine to give a depressed cladding to substrate tube index difference of Δ^-~0.2 percent, the total materials dispersion will cancel the waveguide dispersion at 1.31 μm. The total Δ is 0.5 percent which guarantees tight mode confinement. The core diameter of 7.5 μm gives a cutoff wavelength of ~ 1.25 μm. Fig. 1(c) shows the idealized index profile and defines Δ^+ and Δ^-. The measured profile of a fiber made to this design is shown in Fig. 4 [29].

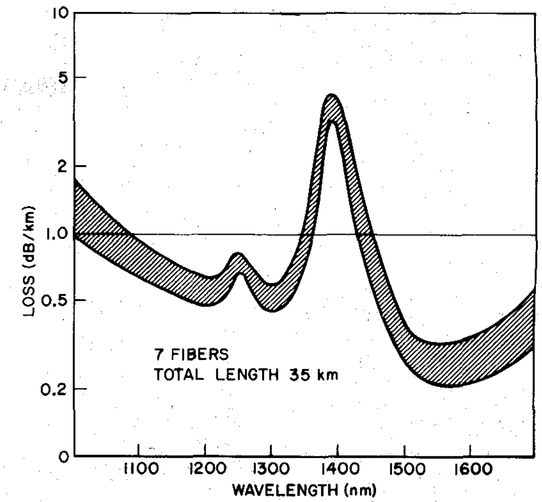

Fig. 3. Envelope of loss curves for 7 fibers of the Type V-F structure having Δ ~ 0.35 percent, $\Delta' \leqslant 0$ percent, 9 μm core diameter, and ~ 110 μm OD. Average fiber loss at 1.30 μm is 0.54 ± 0.11 dB/km.

The ability to control the zero dispersion wavelength is shown in Fig. 5 where the chromatic dispersion, calculated as the derivative of the measured group delay versus wavelength data, passes through zero at λ_0 = 1.312 ± 0.003 μm. Note that the dispersion is below 2 ps/nm · km over a 0.05 μm wavelength range. No curvature induced shifts in λ_0 were detected.

TYPE VI LOSS AND CURVATURE EFFECTS

The spectral loss of a Type VI fiber under low curvature conditions is shown in Fig. 6 as the solid curve. The low OH content and the resulting low loss at 1.39 μm was achieved by using a compensated collapse in which $GeCl_4$ and Cl_2 were added to the gas stream [14]. The overall loss is low as one would expect from the reduced GeO_2 doping level required in this design [30]. At 1.32 μm the loss is 0.40 dB/km and falls to 0.25 dB/km at 1.50 μm. The loss beyond 1.5 μm rises rapidly and is unbounded at long wavelengths. This loss "edge" is due to radiative loss that occurs when the mode effective index n_e is below the substrate index n_s [31]. The effective mode index is the mode propagation constant β divided by $2\pi/\lambda$. The rise in loss begins at a wavelength λ' at which $n_e = n_s$ and increases rapidly for $n_e < n_s$, i.e., for $\lambda > \lambda'$. Note that fundamental mode cutoff occurs when $n_e = n_{\text{clad}}$ and is at a wavelength greater than λ'.

Our 3 dB loop radius test of the curvature induced loss sensitivity indicated lower sensitivity than the high Δ Type V-F fibers. However, in this test only a very short length of fiber experiences the curvature. A more sensitive test is to place a kilometer of fiber under curvature and measure the

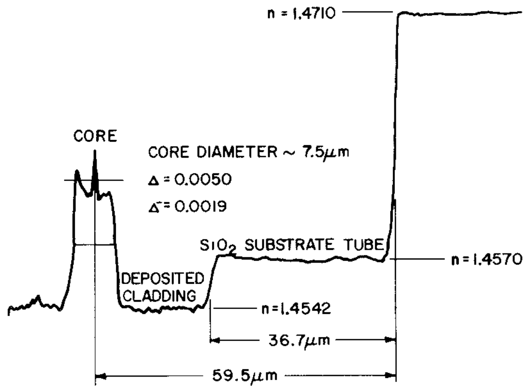

Fig. 4. Index profile of a Type VI single-mode fiber as measured by the refracted near field technique. Some smoothing results from the finite probe beam spot size. The large index step at the right-hand side is the substrate tube to index oil interface.

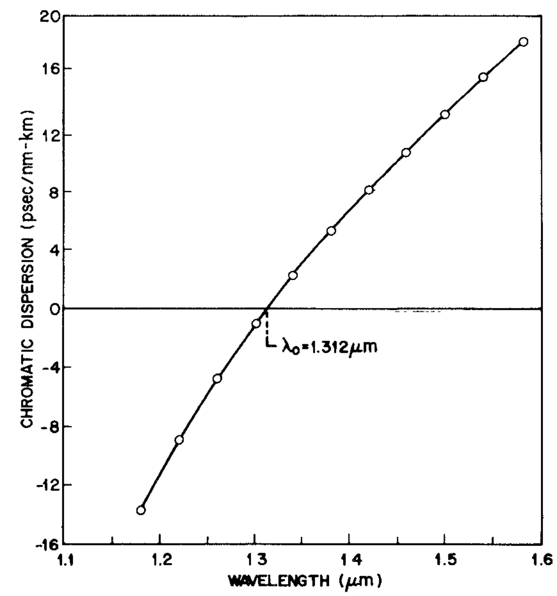

Fig. 5. Dispersion data for a single-mode fiber of the Type VI structure with $\Delta = 0.50$ percent, $\Delta^- = 0.19$ percent, and a 7.5 μm core diameter. The zero dispersion wavelength is 1.312 ± 0.003 μm.

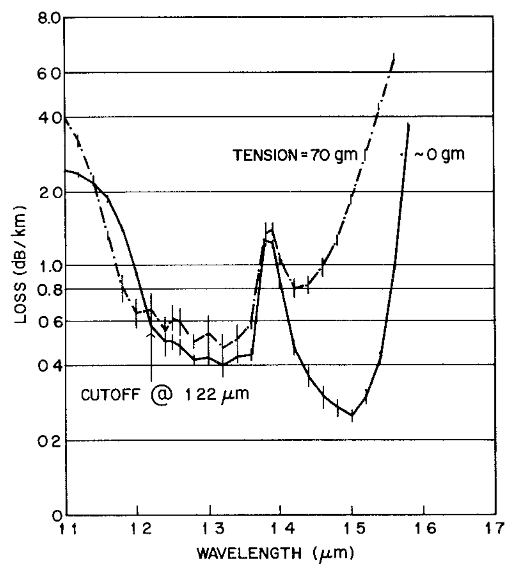

Fig. 6. Loss curve of a single-mode fiber of the Type VI structure with $\Delta = 0.45$ percent, $\Delta^- = 0.17$ percent, and an 8.0 μm core diameter. The solid curve is for the fiber wound under very low tension on a large diameter soft surfaced drum. The dot-dash curve is after winding under 70 g tension on a 150 mm diameter spool. The loss below 1.22 μm is high due to higher mode cutoff. Error bars correspond to 3σ.

change in loss. The "basketweave" test [32] winds a kilometer of fiber in multiple layers, under tension, on a 150 mm diameter spool such that about once each meter, the fiber passes over itself. Fig. 6 (dot dash curve) shows the spectral loss after basketweaving under 70 g tension. A pronounced shift of the loss edge to shorter wavelengths is observed. Near 1.3 μm the loss only increased by an amount equal to the measurement uncertainty, thus confirming the excellent mode confinement we expected for this design.

It is clear that if the initial (low curvature) position of the loss edge is at too short a wavelength, then under curvature the loss edge will shift close enough to 1.3 μm to substantially increase the loss there. Positioning of the loss edge at a sufficiently long wavelength to prevent this is an important requirement. There are three ways to control this: 1) use doped substrate tubes so that $n_s = n_{\text{clad}}$ and there is no leaky mode region, 2) use a large ratio of deposited cladding diameter D to core diameter d, or 3) choose Δ^+ and Δ^- to place λ' at a sufficiently long wavelength. Irven *et al.* [33] have used a D/d ratio of 10 to control λ', but this exacts a processing time penalty due to the large amount of cladding that must be deposited. We have used Δ^+ and Δ^- to control λ'. Fig. 7 shows the loss curves (under low curvature conditions) of fibers from four preforms with different values of Δ and Δ^-; *A*) $\Delta = 0.51$ percent, $\Delta^- = 0.23$ percent; *B*) 0.55 percent, 0.23 percent; *C*) 0.47 percent, 0.19 percent; and *D*) 0.45 percent, 0.17 percent. The data show that as the effective index is raised relative to n_s, λ' moves to longer wavelength. In going from fiber *A* to *B*, Δ^+ was increased and Δ^- was unchanged, while in going from *C* to *D* Δ^- was decreased and Δ^+ was unchanged. Fiber *D* is the same fiber as in Fig. 6.

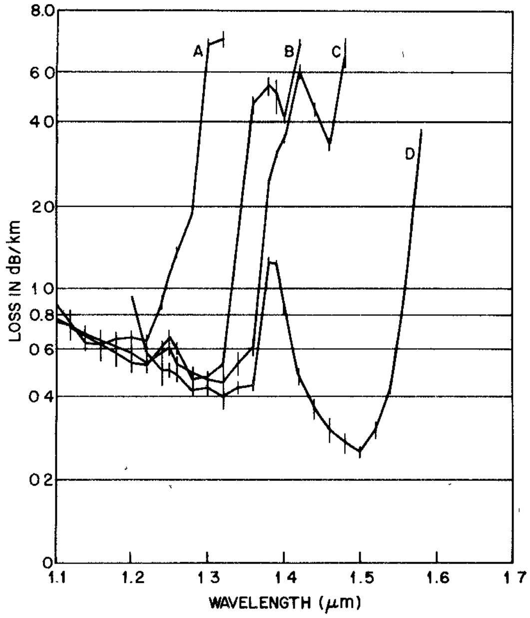

Fig. 7. Loss curves for four fibers of the Type VI structure having the following values for Δ and Δ^-: *A*) 0.51 percent, 0.23 percent; *B*) 0.55 percent, 0.23 percent; *C*) 0.47 percent, 0.19 percent; and *D*) 0.45 percent, 0.17 percent.

It is worth noting that as λ' moves to longer wavelength the higher mode cutoff wavelength λ_c also tends toward longer wavelength as these modes suffer the same leaky mode behavior as the fundamental mode. This also means that the measured λ_c is a function of the length of the test fiber. Fig. 6 shows that curvature shifts λ_c to shorter wavelength as is the case with the Type V and V-F fibers [34].

Type VI Cabling

Several lengths of Type VI fiber have been incorporated into an undersea cable structure [19] for evaluation of the cabling induced losses. The cable was 3 km in length. The loss of each fiber was measured at 1.30 μm both before cabling (wound on 150 mm diameter spools under 20 g tension) and after being incorporated into the cable structure. The results [35] on seven fibers showed a *decrease* in loss of 0.05 ± 0.07 dB/km. The mean loss at 1.30 μm after cabling was 0.52 ± 0.06 dB/km. This indicates essentially no change in loss on cabling and confirms the basketweave results mentioned previously. Environmental tests remain to be performed.

Fiber Strength and Splicing

During recovery operations of an ocean cable for repairs, the cable may be subject to strains up to 0.8 percent. In order to withstand these stresses at any time throughout the cable lifetime an initial proof-test in the range 150–250 ksi will be required. Recently, DiMarcello and co-workers [36] have shown that 8.5 km lengths of "fiber" will pass a 200 ksi proof-test with substantially 100 percent yield, and that lengths as long as 4 km can pass a 500 ksi proof test. These "fibers" were actually Suprasil 2F® rods (a high quality synthetic silica) that were fire polished, drawn into fiber, and coated under carefully controlled laboratory conditions. We would expect a similar result for carefully prepared lightguide preforms made from synthetic silica tubes, and drawn and coated under clean well-controlled conditions.

It is probable that repeater spans of 35–50 km will require the use of high strength fiber splices. Krause and co-workers [37], [38] have shown that single-mode fiber splices can be made with mean strengths of 600 ksi. These high strength splices have been shown to have median added loss at 1.3 μm of 0.20 dB [39]. These splices were of Type V-F fibers with a 7.5 μm core diameter. Further loss reduction may be possible as fiber splicing techniques improve.

Summary

This paper has discussed a progression from large core low Δ designs which showed unacceptably high bending losses, to small core high Δ designs which showed very low bending losses but only moderate bandwidths, to intermediate core diameter, moderate Δ designs which show high bandwidths and may have acceptable cabling induced loss performance. The culmination has been the Type VI design which shows very high bandwidth and extremely low curvature induced loss and appears well suited not only for undersea cable systems, but also for possible use in future high data rate long-haul terrestrial lightguide systems. This type of fiber is unique in allowing independent choice of spot size and zero total dispersion wavelength for a given cutoff wavelength.

Finally, it is worth mentioning that all of the fibers described in this paper have been fabricated on the same MCVD machine using the same chemical delivery system and control equipment. The versatility of the MCVD preform preparation technique in handling a variety of chemicals and compositions over a large range of delivery rates is notable.

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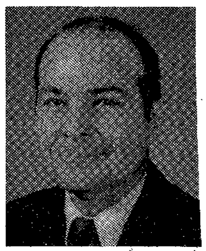

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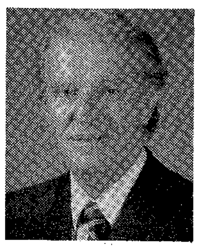

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