THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 61, No. 3, March 1982
Printed in U.S.A.

B.S.T.J. BRIEF

Experimental Verification of Ultra-Wide Bandwidth Spectra in Double-Clad Single-Mode Fiber

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(Manuscript received December 23, 1981)

The low-loss and low-dispersion properties of single-mode fibers make them obvious choices for wide bandwidth system applications with very long repeater spans. This brief describes the fabrication procedure and transmission properties of a double-clad single-mode fiber which is capable of wide bandwidth (greater than 100 GHz-km for laser sources with 4-nm emission bandwidths) transmission over the widest wavelength range (1.45 μm to 1.73 μm) thus far reported in the literature. This range completely covers the lowest-loss wavelength window for fused-silica optical fibers. Double-clad lightguides[1-4] were formed by using an inner cladding to form an index well between the core and a pure silica outer cladding. A computer-aided analytical procedure was used to choose the proper fiber diameter so that waveguide dispersion effects could be used to cancel material dispersion at predetermined wavelengths.[5]

The modified-chemical-vapor-deposition (MCVD) technique was used for preform fabrication. Sixty outer cladding layers, a composition of GeO_2-P_2O_5-SiO_2 and fluorine, having the same refractive-index as pure silica were deposited by the MCVD method inside a 16- by 20-mm fused silica tube. The composition of six inner cladding layers is fluorine-doped silica in order to maintain a 0.35 percent negative index difference relative to the outer cladding. Then six core layers of GeO_2-SiO_2

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composition having a 0.55 percent positive index difference relative to the outer cladding were deposited. The refractive-index profile and diameter of the preform were measured by the laser beam refraction technique.[6] Figure 1 shows the refractive-index profile of a double-clad lightguide preform. The usual dopant burn-off from the center of the core during the high temperature collapsing step caused profile deviations from an intended step-index shape. The fiber was drawn from the preform at 2100°C using an RF-induction zirconia furnace and coated by a 50-μm-thick UV-curable acrylate resin (EA-II) immediately after exiting from the furnace.

The preform index profile data in Fig. 1 were used in a computer analysis program[5] to predict dispersion and bandwidth spectra for single-mode fibers. The optimal fiber diameter, 2a = 11 μm, was calculated to achieve the highest possible transmission bandwidths over the widest possible band of wavelengths within the lowest loss window for fused silica optical fibers. Calculated results in Fig. 2 show how dispersion effects caused by the structure of the double-clad waveguide (curve . . .) can be apportioned to cancel dispersion effects caused by germania and fluorine-doped fused silica materials (curve - - - -). Results obtained by summing points on those two curves predict the total chromatic dispersion (curve ——) if the preform profile in Fig. 1 is drawn into a fiber with a diameter of 2a = 11 μm.

Figure 3 plots measurements of group delay versus wavelength obtained from 1-km-long fibers that were drawn from the preform characterized in Fig. 1. Fiber No. 1 had a diameter of 2a = 11 μm and Fiber No. 2 had a diameter of 2a = 13.2 μm. The curves were fitted to the data using a least-mean-square-fit method.[7] Figure 4 shows chromatic dispersion spectra obtained by differentiating the curve shown in Fig. 3. The predicted (curve . . . .) and measured (curve ——) values of chromatic dispersion for the optimal fiber core diameter (2a = 11 μm) agree closely. Notice that the fiber dispersion is less than 0.665 ps/ km × nm between the two spectral zero crossings at $\lambda = 1.495$ μm and 1.666 μm. This low-dispersion spectral range, for Fiber No. 1, is nearly 2.5 times wider than for the curve, labeled Miya et al.,[4] corresponding to the best previously published result. Figure 5 shows transmission bandwidth spectra transformed[7] from chromatic dispersion spectra in Fig. 4. Results are applicable if Fibers No. 1 and No. 2 are excited by a laser source with a 4-nm linewidth and can be rescaled for different linewidths. Notice that bandwidth values for Fiber No. 1 are larger than 100 GHz-km for all wavelengths spanning the region from 1.45 μm to 1.73 μm. Low loss values were maintained simultaneously with low dispersion. Specific loss values were 0.8 dB/km at $\lambda =$ 1.3 μm, 0.4 dB/km at $\lambda = 1.6$ μm, and 4 dB/km near the center of the water absorption peak at $\lambda = 1.39$ μm.

The importance of choosing optimal lightguide parameters can be appreciated by making comparisons between the dispersion and bandwidth spectra of Fiber No. 1 (solid line) and Fiber No. 2 (dashed line). Fiber No. 2, which has a cladding diameter (2a) about 2.2 μm (or 20 percent) larger than the optimal value, shows only one zero dispersion wavelength. As a result, 100 GHz-km bandwidth values can be maintained only within a 0.026-μm wavelength range that is an order of magnitude narrower than the corresponding 0.28-μm wavelength range for the optimal Fiber No. 1.

In conclusion, this brief reports the fabrication procedure and transmission properties of a double-clad fiber which has potential for wavelength-division-multiplexing applications within wide wavelength ranges. A computer analysis program was used to determine the optimal lightguide diameter which demonstrated high bandwidths over the widest range of wavelengths (1.45 μm to 1.73 μm) published to date. Further efforts are concentrating on fabricating fibers whose high bandwidth spectra cover the band from 1.3 μm to 1.55 μm.

ACKNOWLEDGMENTS

We thank K. D. Pohl of Western Electric Company's Engineering Research Center for preform fabrication, and P. J. Lemaire of Bell Laboratories for stimulating discussions.

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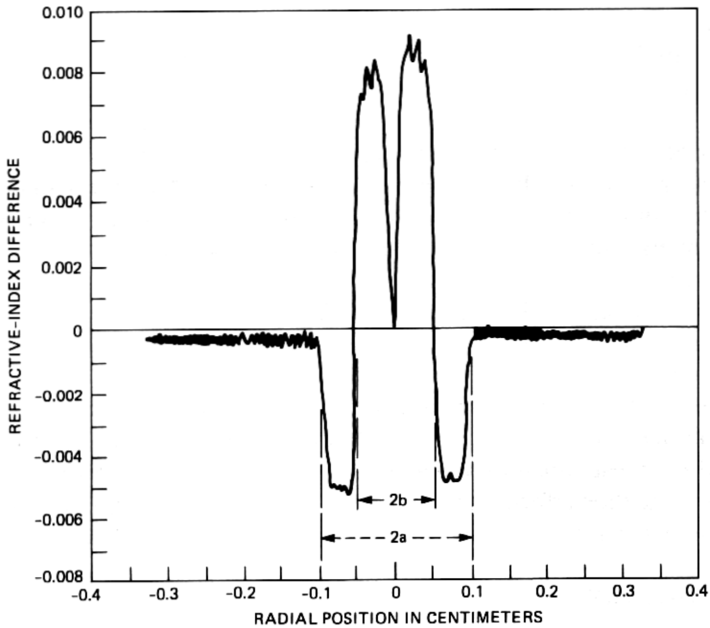

Fig. 1—Refractive index profile of a double-clad single-mode fiber preform measured by the laser beam refraction technique.

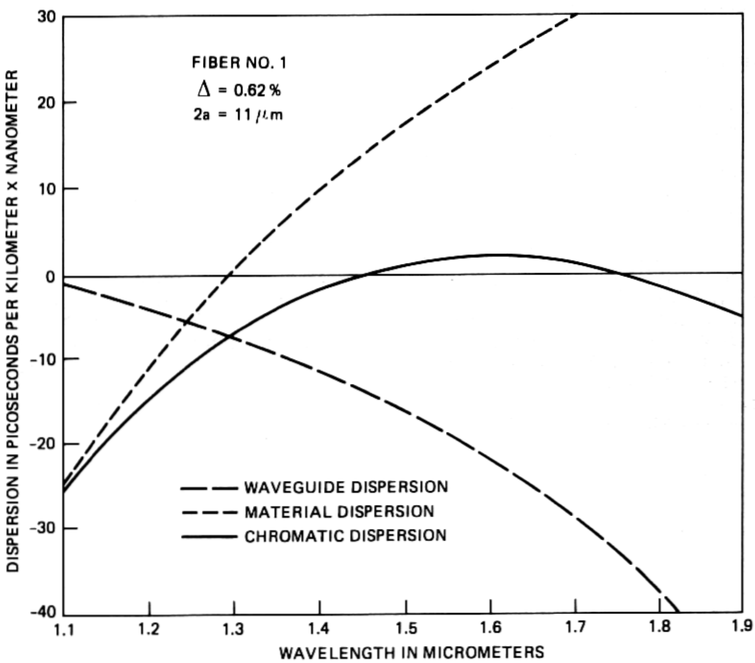

Fig. 2—Dispersion spectral components predicted if the preform profile in Fig. 1 is drawn into a fiber with 2a = 11 μm diameter.

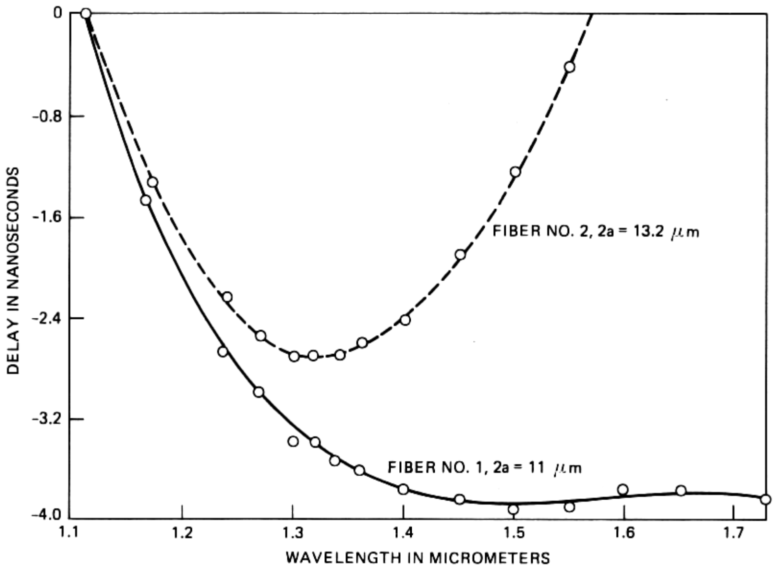

Fig. 3—Group delay spectra from 1-km length of Fibers No. 1 (2a = 11 μm) and No. 2 (2a = 13.2 μm).

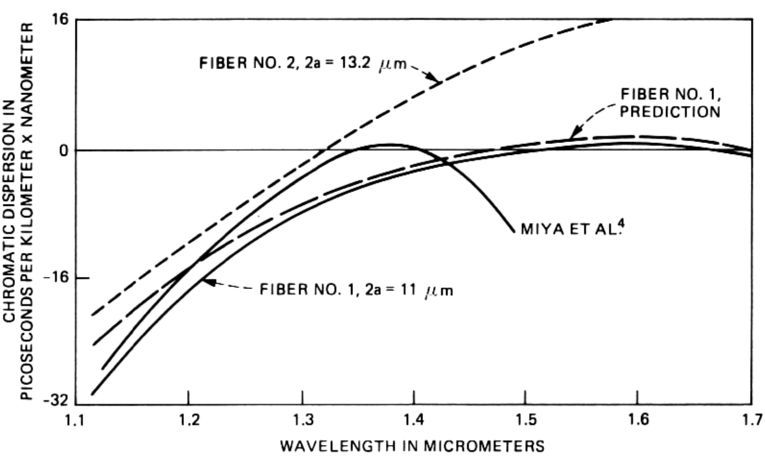

Fig. 4—Chromatic dispersion spectra calculated from Fig. 3 and predicted chromatic dispersion spectrum for diameter 2a = 5.5 μm (dotted line).

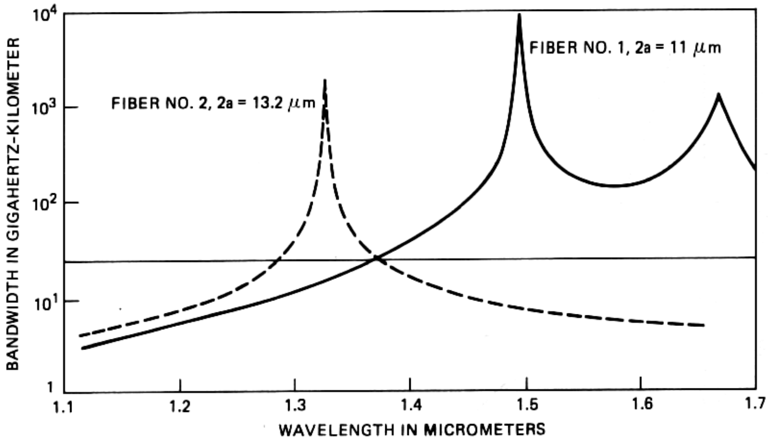

Fig. 5—Bandwidth spectra calculated from Fig. 4.