THE BELL SYSTEM TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING ASPECTS OF ELECTRICAL COMMUNICATION

Volume 60 | October 1981 | Number 8

Transmission Studies of a Long Single-Mode Fiber—Measurements and Considerations for Bandwidth Optimization

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(Manuscript received March 12, 1981)

Loss and bandwidth spectra were measured in the longest length of single-mode MCVD *fiber drawn to date. The 21.7-km-long fiberguide has a 0.5 percent index difference between its 7-μm-diameter core and cladding. Chromatic dispersion effects resulted in a minimum dispersion at a wavelength near 1.35 μm. At 1.30 μm, the fiber loss and bandwidth were measured at 1 dB/km and 21 GHz-km (source linewidth = 4 nm), respectively. Potential system performance was estimated from calculations of dispersion power penalties and chromatic-dispersion-limited repeater spacings for 274- and 548-Mb/s data transmission rates. A new numerical parametric study was used to show how the bandwidth of a fiber can be optimized by properly choosing its core diameter and core-to-cladding index difference.*

I. INTRODUCTION

The high bandwidths and low losses of single-mode fibers make them leading contenders for use in future wideband undersea cable systems.[1] These systems are expected to transmit at 274 Mb/s between repeater stations that will be approximately 35 km apart.

In anticipation of future need for long lengths of single-mode fiber, the modified chemical vapor deposition (MCVD) preform fabrication process has been scaled up. By using 19- by 25-mm support tubes 4 ft long, and glass deposition rates of 0.5 g/min, very large preforms can be made in reasonable times. Each preform yields up to 40 km of fiber.[2]

The purpose of this paper is to present the results of transmission measurements made on a 21.7-km fiber—the longest continuous MCVD fiber drawn to date. Improved automated test set-ups were used to measure loss and dispersion spectra in the 1.06- to 1.7-μm wavelength region.[3,4] Group-delay measurements were used to determine the minimum dispersion wavelength of the fiber. Bandwidth spectra, calculated from group-delay measurements, were compared to direct measurements of pulse broadening due to light sources with 4-nm emission linewidths.[5] Potential system performance was estimated by using the baseband frequency response of the fiber to calculate dispersion power penalties and chromatic-dispersion-limited repeater spacings for 274- and 548-Mb/s data rates.[6,7] Finally, results from a numerical study were used to suggest more optimal waveguide parameters for future fibers that could have higher bandwidths in the vicinity of 1.3-μm wavelength.

II. FIBER PROPERTIES

Transmission characteristics were obtained from measurements of the fiber when it was wound on a foam-covered, 11-in.-diameter support drum. The 21.7-km-long fiber was overwound on the drum in layers of about 1 km/layer. This configuration may have introduced some external microbending and curvature effects in the fiber. As a result, the measured transmission loss may be slightly higher and the measured cut-off wavelength for the second propagating mode may be slightly shorter than if the fiber had been perfectly straight.

Figure 1 shows the fiber loss spectrum which was obtained by using an improved automated test system.[3] Curves are drawn on linear scales representing loss (in dB/km) versus wavelength (in μm). The dashed curve was drawn tangent to the measured curve to illustrate the region where loss decreases with a λ^{-4} wavelength dependence that is characteristic of intrinsic Rayleigh scattering. The rapidly increasing slope of the measured curve for wavelengths shorter than 1.1 μm indicates that the cut-off wavelength for the second propagating mode is near 1.1 μm. The 0.14 dB/km water-related loss peak at 1.24 μm is normally about 20 times lower than the water peak (approximately 2.8 dB/km) near $\lambda = 1.39$ μm.[8] The minimum fiber loss values are 1 dB/km in the 1.3-μm region and 0.78 dB/km in the 1.55-μm wavelength region. Intrinsic low loss values of 0.5 dB/km at $\lambda = 1.3$ μm and 0.2 dB/km at $\lambda = 1.55$ μm have been reported in the literature.[9]

Dispersion and bandwidth data were obtained with a measurement set that can automatically select narrow pulses from within the almost continuous 1.06- to 1.7-μm range of wavelengths emitted by a fiber

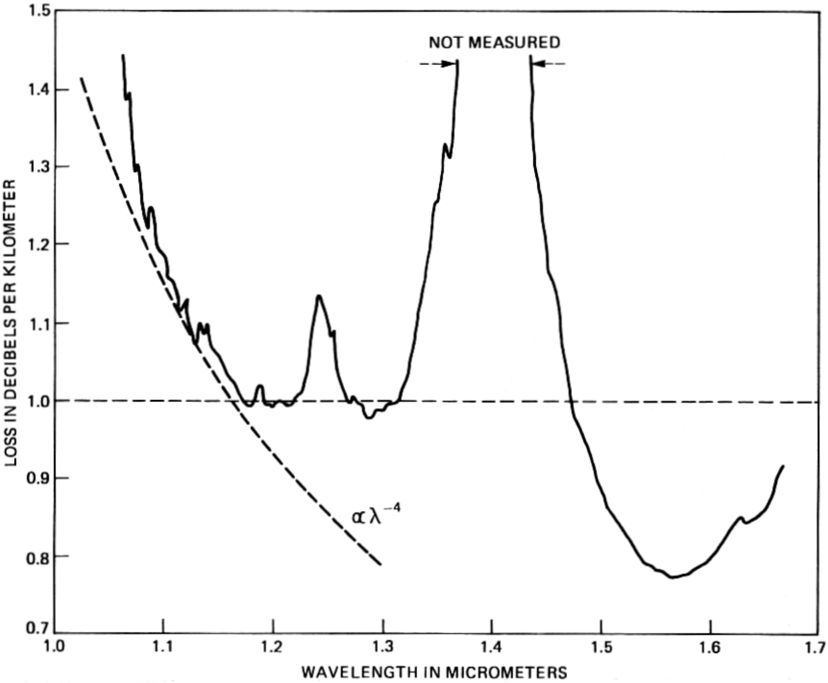

Fig. 1—Fiber loss spectrum plotted on linear scales. The dashed curve is drawn tangent to the measured curve to illustrate the region where loss decreases with a λ^{-4} wavelength dependence.

Raman laser souce.[4] Data are acquired, processed, and displayed by a microcomputer. The system uses an experimental InGaAs photodiode[10] (risetime < 80 ps, bandwidth > 4.25 GHz), which can resolve pulses narrower than the pulse emitted by the laser source (risetime ~ 120 ps, bandwidth ~ 3 GHz).

Figure 2a illustrates group delay spectral measurement results. They were used to calculate the chromatic dispersion spectrum in Fig. 2b, as well as the bandwidth spectrum (the solid line in Fig. 2c). Note, in Fig. 2a, that chromatic dispersion effects in this long fiber length cause large propagation delay changes between pulses at different wavelengths. For example, pulses near $\lambda = 1.35$ μm arrive almost 60 ns earlier than pulses near $\lambda = 1.12$ μm. Minimum chromatic dispersion occurs at a wavelength near 1.35 μm. The bandwidth spectrum in Fig. 2c applies to a laser source with a 4-nm linewidth, propagating within a fiber with negligible polarization dispersion. However, a slightly elliptical core and or strain-induced birefringence effects could cause propagation delay differences between orthogonally polarized components of the LP(01) mode which would limit the maximum bandwidth in (c) to a value below 1000 GHz-km.[11]

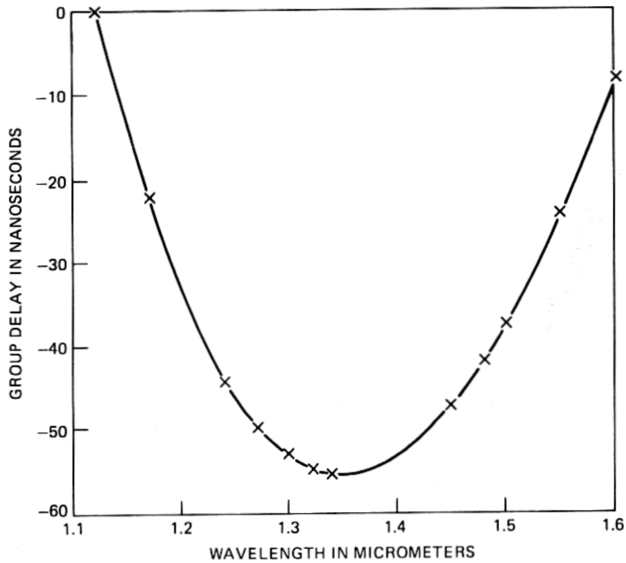

Fig. 2a—Group delay spectrum. The solid curve was fitted to the measured x data points by using a least-mean-square-fit procedure.

The procedure, by which group-delay measurements are used to calculate bandwidth spectra,[5] has proven to be a very convenient way of measuring the performance of short fiber lengths (i.e., as short as 0.5 km) that cannot be characterized from pulse broadening measurements. The 21.7-km, single-mode fiber described is long enough to cause significant pulse broadening which can be used to assess the validity of the bandwidth spectrum in Fig. 2c. The circular points represent bandwidth values that were obtained by transforming pulse

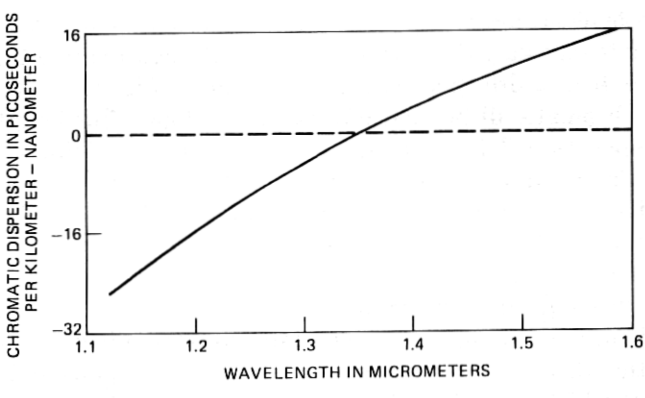

Fig. 2b—Chromatic dispersion spectrum calculated from Fig. 2a. The minimum dispersion wavelength is located at $\lambda = 1.35\ \mu m$.

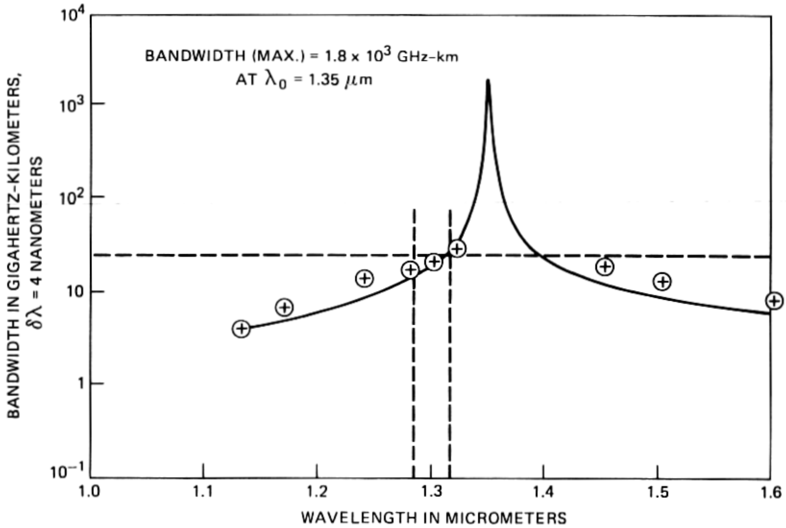

Fig. 2c—Bandwidth spectrum for a source with a 4-nm spectral linewidth. The solid curve was calculated from the values and slopes of the chromatic dispersion spectrum in Fig. 2b. The 0 data points were obtained from pulse broadening measurements. The dashed horizontal line represents the 25-GHz-km bandwidth level which is required to avoid equalization in a regenerator for 274-Mb/s data transmission. The dashed vertical lines represent the range of allowed laser wavelengths for a proposed undersea lightwave cable system.

broadening data. They are in excellent agreement with the solid bandwidth spectrum that was deduced from group delay measurements.

Figure 3 illustrates broadened output pulses at five different wavelengths when the Raman laser output light was filtered to have a 1-nm spectral width. The horizontal time scale is 1 ns/division for $\lambda = 1.06$-μm wavelength and 0.4 ns/division for the other wavelengths. The double-peaked pulse shape at $\lambda = 1.06$ μm is indicative of two-mode propagation.[12] The remaining pulses have only one peak which implies that the cut-off wavelength for the second mode lies between 1.06 and 1.12 μm. That result is consistent with the 1.1-μm-wavelength value which was deduced from the loss spectrum (Fig. 1). Note too, that the pulsewidth becomes narrower as the wavelength increases towards the minimum dispersion wavelength at $\lambda = 1.35$ μm. The pulsewidth at $\lambda = 1.6$ μm is broader than the one at $\lambda = 1.3$ μm because the former is displaced further from $\lambda = 1.35$ μm.

Figure 4 illustrates impulse responses obtained at $\lambda = 1.3$ μm by using 1-nm- and 5-nm-wide spectral filters for (b) and (c), respectively. The resolution of the output pulse shapes was limited by the 100-ps risetime and 3-GHz bandwidth of the input pulse in (a). Fiber bandwidths were obtained from output/input FFT (fast Fourier transform)

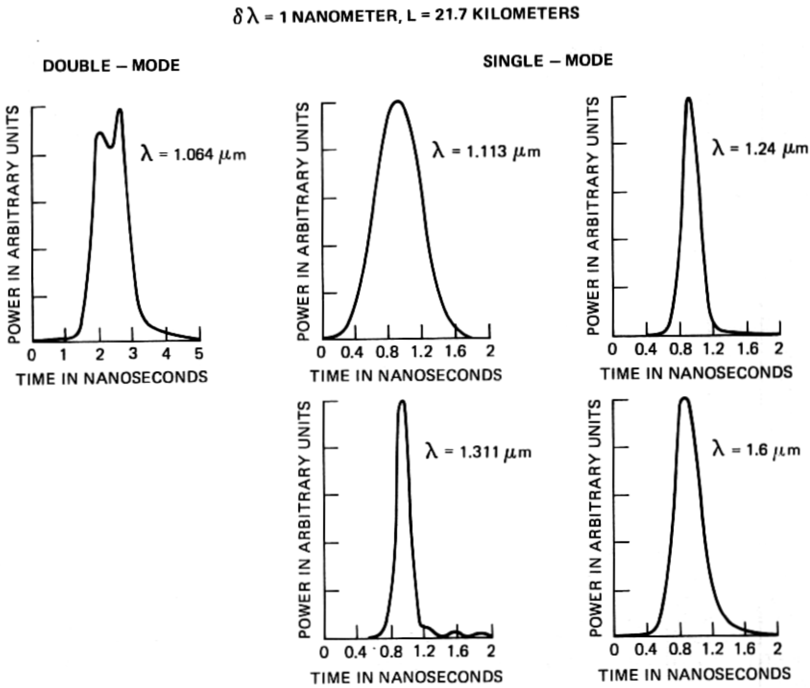

Fig. 3—Broadened output pulses at five different wavelengths. The horizontal time scale is 1 ns/division at $\lambda = 1.06$ μm and 0.4 ns/division at the other wavelengths. The twin-peaked pulse at $\lambda = 1.06$ μm indicates double-mode propagation.

ratios calculated from the pulse shapes. The inset graph plots bandwidth results versus the inverted spectral width of the filtered Raman laser source. They confirm that the fiber bandwidth increases linearly[5] with the inverse of the source linewidth, from 5 nm to 1 nm, because the 1.3-μm test wavelength is significantly different from the minimum chromatic dispersion wavelength at 1.35 μm. However, the linear extrapolation cannot be extended indefinitely to very narrow linewidths which would make the fiber bandwidth very large. In practical situations, the maximum bandwidth is limited by polarization dispersion effects caused by small propagation delay differences between orthogonally polarized components of the LP(01) mode.[11] The maximum bandwidth measured in this study was 90 GHz-km in 1.32-μm-wavelength light with a $\delta\lambda$ = 1-nm-rms linewidth. A bandwidth of 71 GHz-km was independently measured using an Nd:YAG laser which has a spectral linewidth $\delta\lambda < 0.05$ nm.[13] Therefore, bandwidths did not scale with source linewidths less than 1 nm, implying that the maximum bandwidth of this fiber is about 90 GHz-km. This limit may be imposed by polarization dispersion. Further investigation will be required to validate this conjecture and to determine whether polarization dispersion effects, if any, are caused by core ellipticity or by strain-induced birefringent effects at the core-cladding interface.

Semiconductor injection laser sources typically have 4-nm spectral linewidths in the 1.3-μm wavelength region. Lasers of this type are being proposed for use in undersea telecommunication systems whose repeater spacings will be approximately 35 km. Results in Fig. 2c indicated that the normalized fiber bandwidth is 21 GHz-km (actual bandwidth would be 600 MHz for a 35-km propagation length). The next section will show that those bandwidth characteristics should be suitable for use in systems transmitting at 274-Mb/s data rates.

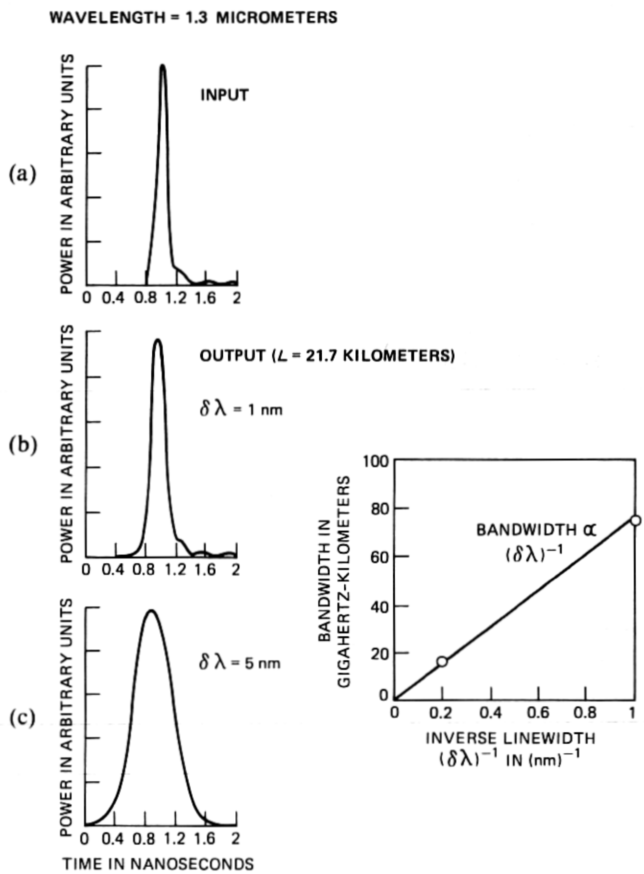

Fig. 4—Impulse response at $\lambda = 1.3$ μm. The horizontal time scale is 0.4 ns/division. (a) Input pulse (risetime ~120 ps, bandwidth ~3 GHz). (b) Output pulse measured within a 1-nm source spectral linewidth. (c) Output pulse measured within a 5-nm source spectral linewidth. The inset graph plots bandwidth versus reciprocal spectral width of the source.

III. ESTIMATES OF SYSTEM PERFORMANCE

In a pulse-code-modulation communication system, pulse spreading causes intersymbol interference in the form of overlapping pulses. In principle, those pulses can be separated by equalization or high-frequency enhancement in the receiver. However, that enhancement also increases receiver noise which reduces the receiver sensitivity relative to the dispersion-free case. Therefore, system degradation because of dispersion effects can be assigned noise penalties, in dB, which add to fiber transmission losses to give the total lightwave cable loss. Repeater spacings can then be calculated by comparing cable losses with the difference between the optical power levels available and the power levels required for a specified error probability at various data rates.

Optical power penalties, D_p, caused by dispersion are calculated as follows:[7]

$$D_p(\text{in dB}) = 5\log\left\{\frac{1}{J_3}\left[J_3 + \left[\frac{1}{b_2} + C_1\right]B^2J_4 + \left[\frac{C_1}{b^2} + C_2\right]B^4J_5 + \left[\frac{C_2}{b^2} + C_3\right]B^6J_6 + \left[\frac{C_3}{b^2}\right]B^8J_7\right\}, \quad (1)$$

where

B = transmission bit rate,
$b = 1.2$ GHz = electrical 3-dB modulation bandwidth of the laser source,
$C_1 - C_3$ = coefficients that are used to approximate the fiber's baseband frequency response, $|H_c|$, with a polynomial as follows: $1/|H_c|^2 = 1 + C_1f^2 + C_2f^4 + C_3f^6$,
$J_3 - J_7$ = tabulated coefficients for equalizing the receiver passband from a non-return to zero (nrz) input to a raised cosine signal spectrum.

Figure 5 illustrates how to relate fiber transmission bandwidth with the dispersion power penalty, D_p. The vertical axis on the left applies to the D_p versus wavelength curve, while the vertical axis on the right corresponds to the bandwidth spectrum. The magnitude of D_p increases approximately quadratically with L. The illustrated spectral curve is applicable to 274-Mb/s data-rate transmission within a 40-km cable length, which is within the range of proposed repeater spacings for future undersea systems. Comparisons between the two curves in Fig. 5 show that 274-Mb/s transmission rates require that the fiber bandwidth be greater than 274 MHz to keep the system dispersion power penalty below 1 dB, whereas the fiber bandwidth has to be greater than 750 MHz to keep the dispersion penalty below 0.2 dB. The former specification can be generalized in the following interesting

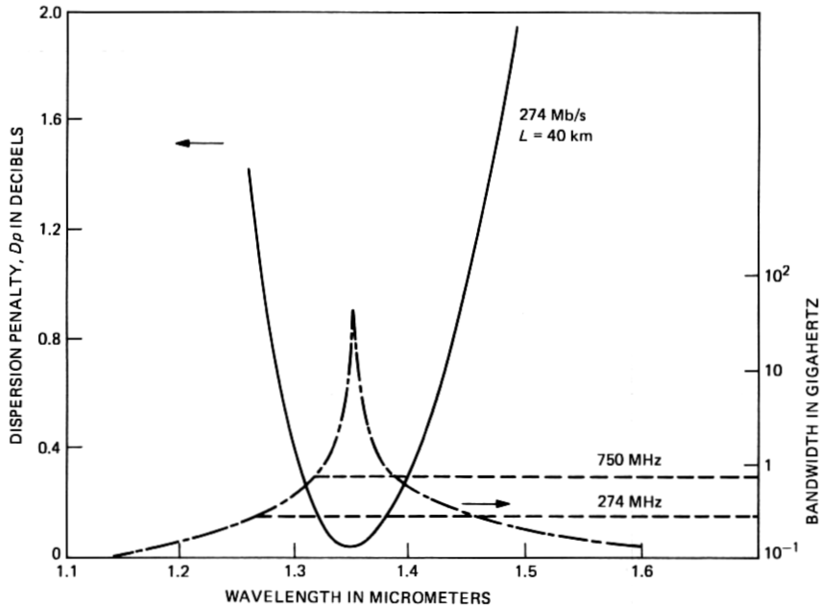

Fig. 5—Dispersion power penalty spectrum (solid curve) for 274-Mb/s systems (left-hand scale). Bandwidth spectrum (dashed curve, right-hand scale). The dashed horizontal lines show that the fiber bandwidth must be greater than 274 or 750 MHz to keep the corresponding dispersion penalty below 1 dB or 0.2 dB, respectively.

way. If the bandwidth of a fiber is equal to the bit rate of a system, then the resultant dispersion power penalty will be about 1 dB because of intersymbol interference. The $D_p = 0.2$ dB specification would be very desirable to meet because the penalty is small enough to ensure that no equalization would be necessary in any of the numerous regenerators that would be required for a long distance telecommunication system.

Results similar to those shown in Fig. 5 were generated for different fiber lengths so that chromatic-dispersion-limited repeater spacings could be calculated as a function of wavelength. Results shown in Fig. 6 indicate solid curves which apply for 274-Mb/s data rates, as well as dotted curves which apply for 548-Mb/s data rates. The vertical dashed lines indicate the wavelength limits, 1.3 ± 0.015 μm, which give a margin for source wavelength deviations around a 1.3-μm nominal system wavelength. The outer solid and dotted curves were calculated to keep $D_p < 1$ dB, while the inner curves were calculated to restrict $D_p < 0.2$ dB. The results show that repeater spacings for $B = 274$ Mb/s could range between 24 km and 54 km, depending on the dispersion penalty allowed. By comparison, for $B = 548$ Mb/s, the repeater spacing could be 24 km if $D_p = 1$ dB, but would be much shorter if smaller dispersion penalties are required.

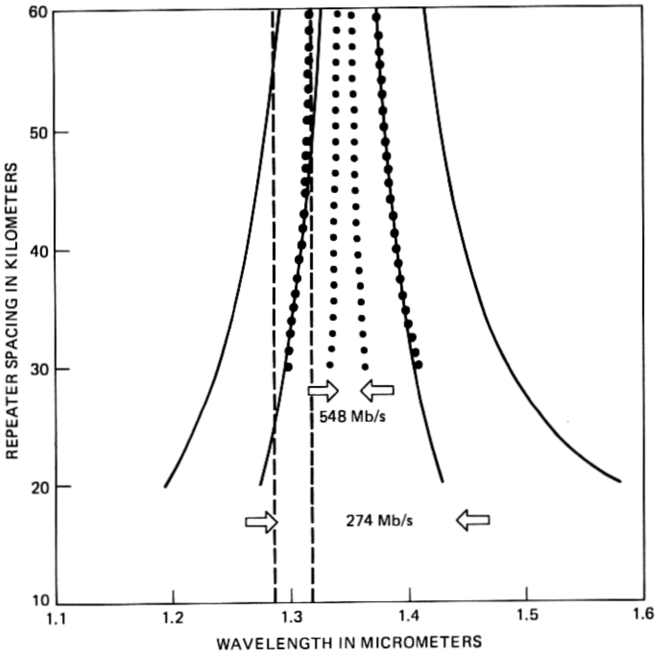

Fig. 6—Chromatic-dispersion-limited repeater spacings plotted versus wavelength. The solid curves apply to 274-Mb/s systems and the dashed curves apply to 548-Mb/s systems. The inner (solid and dotted) curves were calculated to maintain $D_p = 1$ dB; while the outer curves maintain $D_p = 0.2$ dB. The dashed vertical lines represent the allowed range of laser wavelengths.

The curves in Fig. 6 indicate that the 21.7-km fiber under study should meet the bandwidth requirements for 274-Mb/s systems with 35-km repeater spacings provided that each regenerator is individually equalized. Potential repeater spacings could be significantly lengthened if the minimum dispersion wavelength could be moved closer to the operating system wavelength at 1.3 μm.

IV. SUGGESTIONS FOR OPTIMIZATION

This section describes results of a numerical study to determine a more optimal structure that would make future fibers have higher bandwidths near $\lambda = 1.3$ μm. Results were generated from numerically exact solutions for the LP(01) propagating mode of the scalar wave equation as indicated in a companion publication.[5] Figure 7 summarizes the results with curves of bandwidth (source linewidth = 4 nm) at $\lambda = 1.3$ μm as a function of fiber core diameter, d. A step-index profile shape was assumed for various core-to-cladding index differences, Δ, which served as variable parameters for the curves. If future experimental fiber profiles are found to conform to a universal shape, other than step-index, then future parametric studies could be modified accordingly. Therefore, the curves in Fig. 7 should be viewed as qualitative. They indicate that fiber bandwidths at $\lambda = 1.3$ μm can be increased by increasing $V = (\pi d/\lambda)n\sqrt{2\Delta}$ as long as single-mode behavior is maintained. The range of allowed values lies below the diagonal dashed lines which correspond to constant V-values of 2.4 and 2.7 at $\lambda = 1.3$ μm. The $V = 2.4$ value is the theoretical limit for step-index, single-mode fibers. However, recent measurements indicate that $V = 2.7 = (\pi d/\lambda_{co})n\sqrt{2\Delta}$ is a more accurate value for calculating the cut-off wavelength, λ_{co}, for single-mode operation in experimental fibers.[14]

Fibers with relatively small-core diameters, d, and large index differences, Δ, offer good mode confinement and very good resistance to curvature-induced cabling losses. The 21.7-km fiber, described in this paper, has a nominal core diameter, $d \approx 7.2$ μm, an index difference, $\Delta \approx 0.0051$, and a cut-off wavelength, $\lambda_{co} \approx 1.2$ μm. Higher bandwidths should result if V-values for future fibers are increased by about 8 percent, which is the maximum allowed change that would still maintain single-mode behavior at system wavelengths near 1.3 μm. Results in Fig. 7 indicate that bandwidths will increase most if Δ is kept constant and the fiber diameter is increased. More optimal parameters for future fibers would then be $\Delta \approx 0.0051$ and $d = 7.8$ μm.

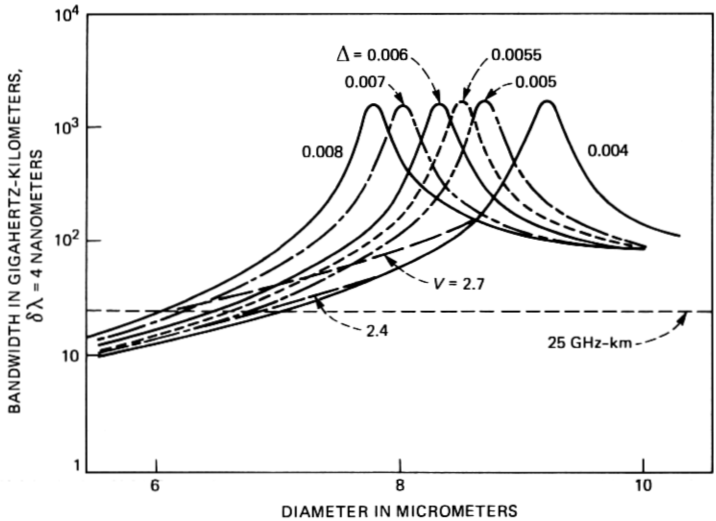

Fig. 7—Parametric study of step-index, single-mode fibers. Bandwidth (source linewidth = 4 nm) at $\lambda = 1.3$-μm wavelength is plotted as a function of fiber core diameter, d, with index difference, Δ, as the variable parameter. The dashed diagonal lines indicate constant V-values of 2.4 and 2.7.

V. CONCLUSIONS

The transmission characteristics of a 21.7-km-long, single-mode fiber have been extensively studied. Prototype automated measuring systems were used to determine the fiber properties across the 1.06- to 1.7-μm wavelength spectrum. All measurements were made when the coated fiber was overwound on an 11-in.-diameter, foam-covered drum. This method of supporting the fiber is not ideal because it may have induced external bending effects that could have raised fiber losses and reduced its cut-off wavelength.

The transmission loss spectrum showed minimum loss values of 1 dB/km and 0.78 dB/km at wavelengths near 1.3 and 1.55 μm, respectively. A small water-related loss peak was evident at $\lambda = 1.24$ μm and implies that the OH absorption peak at $\lambda = 1.39$ μm is approximately 2.8 dB/km. The shape of the fiber loss spectrum curve was used to infer that its cut-off wavelength is near 1.1 μm.

Dispersion and bandwidth characteristics were determined by using two independent measurement techniques. Group delay spectral measurements were used to determine the chromatic dispersion spectrum and locate the minimum dispersion wavelength at 1.35 μm. The bandwidth spectrum was calculated from the dispersion spectrum and was found to be in excellent agreement with pulse broadening effects that were measured at different wavelengths using a variety of spectral filters. Light filtered with a linewidth of 5 nm centered around 1.3 μm was used to closely approximate source characteristics proposed for undersea lightwave cable applications. The normalized fiber bandwidth was measured to be 21 GHz-km with a 4-nm linewidth source centered around 1.3-μm wavelength. A higher bandwidth was measured for a source linewidth of 1 nm. The resultant 90-GHz-km bandwidth was close to a value that was measured with a laser whose spectral linewidth was less than 0.05 nm. One possible explanation for the lack of linear dependence of bandwidth on inverse source linewidth might be that polarization dispersion effects caused by core ellipticity or strain-induced birefringence may have limited the maximum bandwidth of this fiber to about 90 GHz-km, independent of the spectral characteristics of the source. However, the limitation is academic because the measured bandwidth is still adequate for a 274-Mb/s system.

Estimates of system degradation because of intersymbol interference were made by calculating the dispersion penalty or, equivalently, the additional power required in the regenerator to equalize the receiver passband. These calculations were related to fiber bandwidth spectrum characteristics through their dependence on baseband frequency response. One interesting result is that the dispersion power penalty is approximately 1 dB when the 3-dB fiber bandwidth equals the bit rate of the system. By comparison, a 750-MHz fiber bandwidth is required to maintain the dispersion penalty below 0.2 dB for a 274-Mb/s system data rate. The latter penalty is small enough to ensure that no equalization would be required in any of the regenerators. The 21.7-km fiber described in this paper should be able to meet system requirements for transmission at a 274-Mb/s rate between repeaters separated by 35 km.

A numerical study was used to show how the bandwidth of a fiber depends on its core diameter, d, and core-to-cladding index difference, Δ. Results indicate that the bandwidth performances of future single-mode fibers could be significantly improved by increasing their core diameters ($d \approx 7.8\ \mu m$; $\Delta \approx 0.0051$). If that is done, potential repeater spacings might be increased to 75 km, which is the upper limit for 274-Mb/s systems with 0.5-dB/km cabled fiber losses and -38 dBm minimum detectable signals at the receivers. Additional limitations because of mode-partition-noise generated in laser sources have not been considered in this paper.

VI. ACKNOWLEDGMENT

The authors thank T. P. Lee for providing the detector, S. Lumish for computational assistance in obtaining numerical data, and P. D. Lazay for helpful discussions.

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