SINGLE-MODE FIBER: FROM RESEARCH AND DEVELOPMENT TO MANUFACTURING

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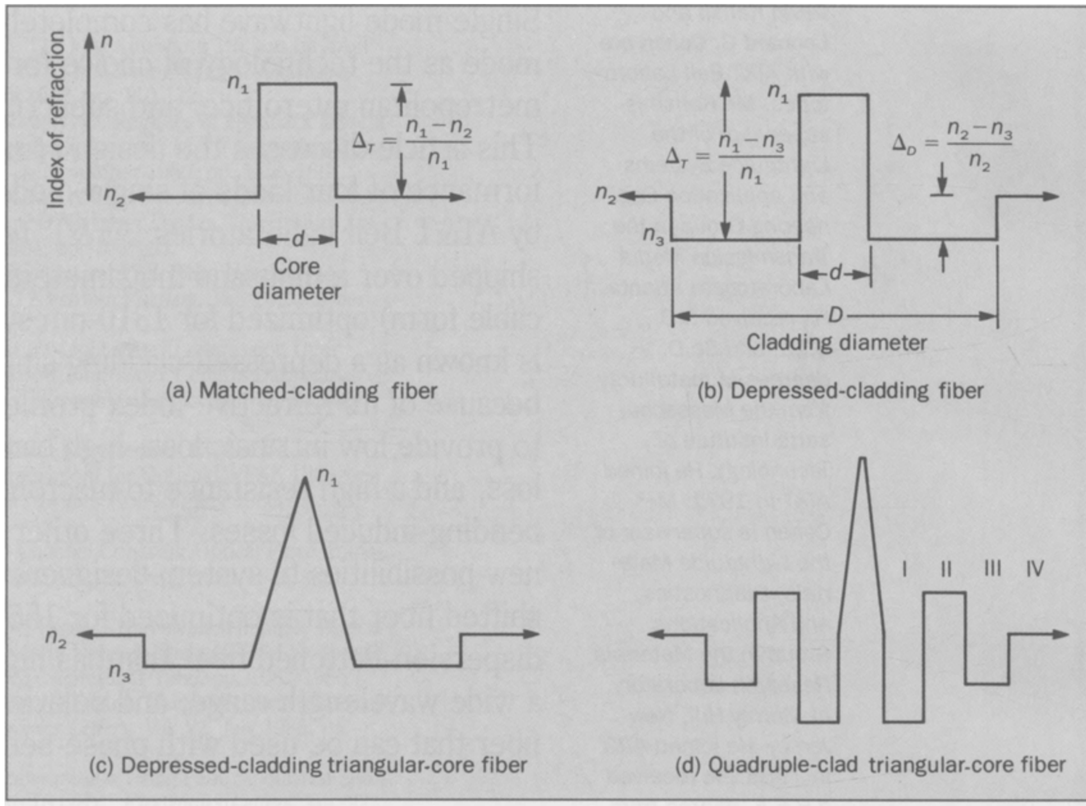
Single-mode lightwave has completely replaced multimode as the technology of choice for long-haul, metropolitan interoffice, and subscriber loop systems. This article discusses the design principles and performance of four kinds of single-mode fibers developed by AT&T Bell Laboratories. AT&T Technologies has shipped over a thousand megameters of a fiber (in cable form) optimized for 1310-nm systems. This fiber is known as a depressed-cladding single-mode fiber, because of its refractive-index profile. It was designed to provide low intrinsic loss, high bandwidth, low splice loss, and a high resistance to macrobending- and microbending-induced losses. Three other fibers that offer new possibilities to system designers are: dispersion-shifted fiber that is optimized for 1550-nm systems; dispersion-flattened fiber that has high bandwidth over a wide wavelength range; and polarization-maintaining fiber that can be used with phase-sensitive receivers.

Introduction

Single-mode technology is now the lightwave technology of choice for high-capacity long-haul, metropolitan interoffice, and subscriber loop feeder systems and is preferred for loop distribution systems under development. The large majority of optical fiber being produced today is single-mode, although multimode fibers are still important for local area networks. This paper will deal exclusively with single-mode fiber because of its dominant role in today's lightwave systems and because almost all research and development on fibers is now devoted to single-mode fiber.

A systematic procedure is being used within AT&T to tailor optical properties of lightguides for specific applications. Dimensions and shapes of refractive-index profiles are initially specified by using a

Figure 1. Single-mode fiber refractive index profiles.



computer-aided analytical procedure to predict optical transmission properties from numerical solutions of the governing electromagnetic equations. The modified chemical vapor deposition (MCVD) process[1-3] is used to fabricate fibers with specified, and sometimes quite complicated, profile shapes as shown in Figure 1. Sensitive diagnostic measurement techniques are then used to interpret experimental results so that the analytical model can be refined in order to optimize fiber properties within a few iterative cycles.

This paper will review the properties of four generic kinds of lightguides. The first kind, step-index core fiber, with matched-index cladding, Figure 1a, or depressed-index cladding, Figure 1b, is currently being manufactured with low losses and nearly zero dispersion at 1310 nm, but rather high dispersion near 1550 nm. These fibers constitute essentially all of the single-mode fiber used to date and will be discussed in some detail in the section "Fibers for 1310-nm Systems." The remaining three kinds of fibers have not found any substantial applications in telecommunications as yet but their special properties offer some interesting potential for system designers. These fibers will be covered more briefly in the section "Fibers for Future Systems."

The second kind, dispersion-shifted fiber, Figure 1c, can be tailored to simultaneously provide low loss and

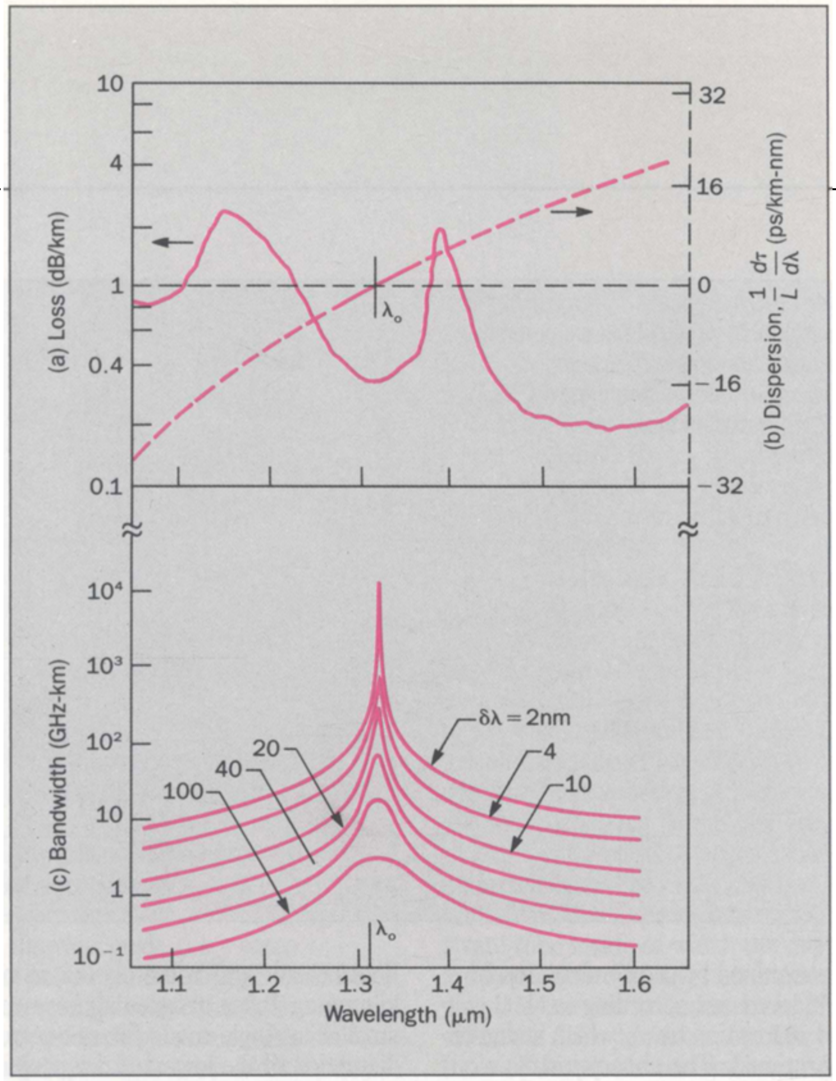


Figure 2. Single-mode fiber transmission characteristics: (a) loss and dispersion versus wavelength, (b) bandwidth-distance versus wavelength calculated from the dispersion for source spectral widths ($\delta\lambda$) from 2 to 100 nm.

almost zero dispersion at a wavelength near 1550 nm. This fiber could be well suited to systems for which there is great economic incentive to maximize the cable span distance between repeaters. The third kind, dispersion-flattened fiber, Figure 1d, has high bandwidth over a wide wavelength range which might encompass both 1310 nm and 1550 nm. Such fibers could be useful for wavelength-division multiplexing many high-bit-rate information channels onto the same fiber. The fourth kind, polarization-maintaining fiber (not shown in Figure 1) can be used with phase-sensitive detection in systems where a fixed state of polarization is required after propagation along multikilometer lengths of fiber. Current applications include ring fiber gyroscopes, interconnection media between lasers and integrated-optical components, and use as polarizing components.

Transmission Media Limitations

Loss and dispersion (low dispersion means high bandwidth) are the principal characteristics that control the performance of high-bit-rate lightwave systems. Single-mode fibers have lower transmission losses than multimode fibers because their lower dopant concentration in the core leads to lower intrinsic loss due to Rayleigh scattering. Figure 2 shows examples of loss, dispersion, and bandwidth characteristics plotted versus wavelength,

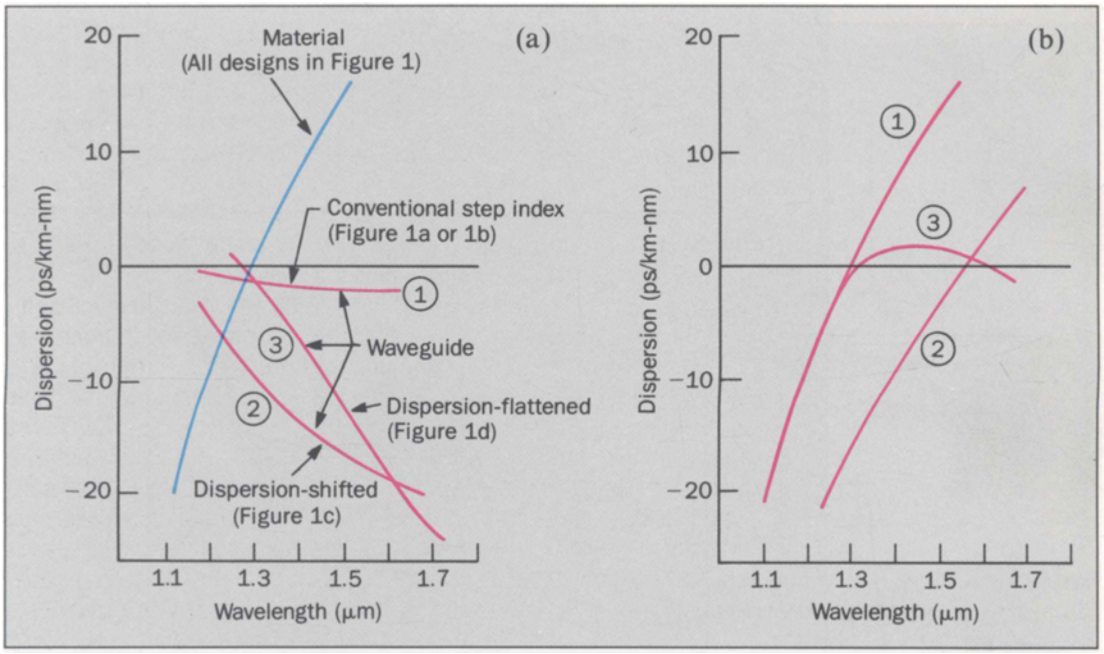


Figure 3. Single-mode fiber dispersion versus wavelength: (a) material dispersion and waveguide dispersion components for various fiber designs, (b) total dispersion.

λ. Minimum losses are determined by the combination of Rayleigh scattering (which decreases according to λ^{-4}) and the tail of the infrared absorption band (which is due to multiphonon molecular vibrations). The absorption of water in the form of OH ions causes an excess loss peak of 1 dB/km at $\lambda = 1390$ nm if the OH concentration is 25 ppb. Additional losses occur because of extrinsic bending effects caused by constant curvature macrobends or by randomly distributed microbend distortions of the fiber axis.

Dispersion effects broaden the width of pulses as they propagate along a fiber. The performance of a pulsed transmission system degrades if the distorted output pulses overlap adjacent time slots to cause intersymbol interference. Dispersion in multimode fibers is dominated by intermodal effects because the hundreds of propagating rays travel different zig-zag paths and therefore arrive at different times at the output. High bandwidth multimode fibers cause approximately 0.2-ns pulse broadening per kilometer. Pulse broadening is several orders of magnitude smaller in single-mode fibers because it is due only to the distortion of the lowest-order propagating mode.

Dispersion in single-mode fibers occurs because spectral components radiating from an optical source [laser or light-emitting diode (LED)] travel with different group velocities in a fiber and therefore arrive at different times at the output end. The total dispersion is actually the sum of two effects, Figure 3a. Material dispersion is a bulk property which occurs because the group velocity of a lightguide mode is a nonlinear function of frequency through the nonlinear dependence of refractive index on wavelength. Zero material dispersion occurs very close to 1310 nm because single-mode fibers are all made from just slightly doped silica glasses. However, the second effect, waveguide dispersion, occurs because the group velocity is also a nonlinear function of frequency through its depend-

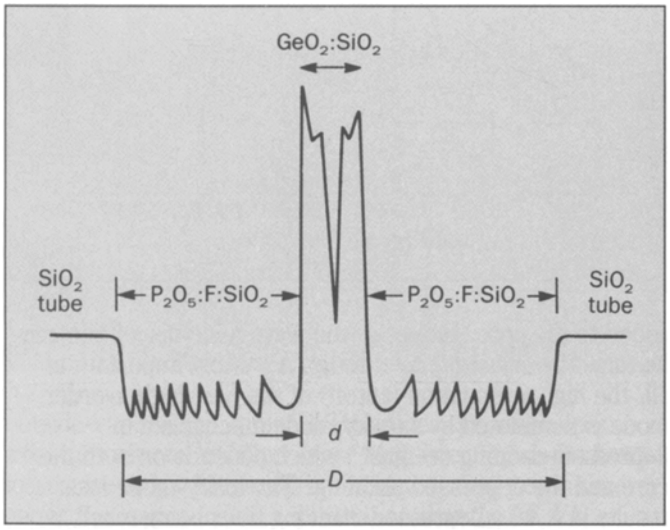


Figure 4. Measured refractive-index profile of AT&T depressed-cladding single-mode preform.

ence on the structure of the waveguide (i.e., core diameter and shape of the refractive-index profile). Thus, the key to controlling dispersion is to use the lightguide structure to tailor the waveguide dispersion so that its shape cancels the material dispersion at one or more wavelengths, Figure 3a. The total dispersion resulting from the addition of material and waveguide dispersion is shown in Figure 3b for three of the generic fiber designs to be discussed (spectrum 1: conventional step index; spectrum 2: dispersion-shifted; spectrum 3: dispersion-flattened).

Fiber for 1310-nm Systems

AT&T has shipped more than a thousand megameters of single-mode fiber in cable and installed nearly 10,000 miles of single-mode cable in its long-haul network. In the 1987-89 timeframe, AT&T will install approximately 10,000 miles of ocean cable with single-mode fiber. A single-mode fiber developed at AT&T Bell Laboratories[4,5] meets the diverse transmission needs and environmental considerations of systems from the subscriber loop to the deep ocean. This fiber was designed for transmission at 1310 nm but can also support transmission in the 1550 nm region. The primary performance requirements for such a fiber are low intrinsic loss and high bandwidth (low pulse dispersion) at 1310 nm. However, there is also a range of other transmission and physical properties that need to be built into this fiber in order to make it practical for engineering applications.

Fiber Designs. An idealized refractive index profile of the AT&T single-mode fiber is shown in Figure 1b and an actual preform index profile is shown in Figure 4. This fiber design is referred to as a "depressed cladding" design because the index of refraction of the inner cladding (next to the core) is "depressed" below that of pure silica. The index control is achieved by co-doping the silica layers deposited in the depressed index region with phosphorus and fluorine; the latter provides the index depression. The index elevation of the core is achieved by doping with germanium alone. The outer cladding (away from the core) in the AT&T MCVD process is simply the initial silica substrate tube inside of which the depressed cladding and core are deposited. The layer structure in the depressed cladding and the central index dip in the core, Figure 4, do not affect the fiber performance. They are reproducible features of the profile that are a consequence of the MCVD process.

The basic objective of the depressed cladding concept is to provide a higher power density and better confinement of the optical power, in order to enhance the resistance to bending-induced losses. Insight into the depressed cladding concept can be obtained by contrasting this design to that of the other step index fiber, Figure 1a, which is referred to as a "matched cladding" design because all of the cladding (everything outside of the core) has an index that "matches" that of silica. These two designs represent essentially all of the single-mode fiber being produced throughout the world to date.

The matched cladding fiber has two profile variables, the index parameter Δ_T and the core diameter d, that

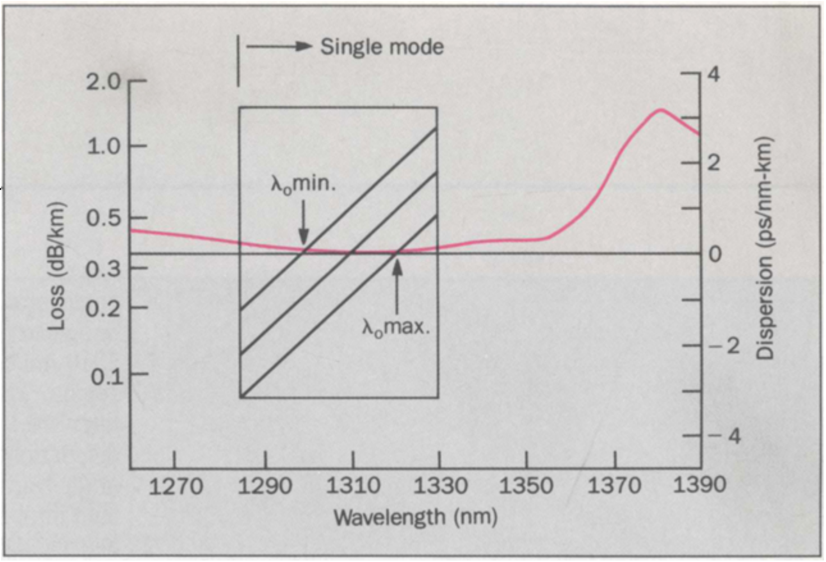


Figure 5. Details of 1310-nm transmission window for AT&T depressed-cladding single-mode fiber.

define the profile and thereby control the lightguiding properties. There are several practical constraints on the values of Δ_T and d in the matched cladding design: (1) $\Delta_T < 0.4$ percent to keep the intrinsic scattering loss low and to avoid fiber-drawing-induced defects that can produce additional absorptive loss; (2) Δ_T and d must be balanced to keep the minimum dispersion wavelength, λ_0, near 1310 nm; and (3) the V number $\leqslant 2.405$ for single-mode operation where $V = (\pi d n_1/\lambda)(2\Delta_T)^{1/2}$. A target V number somewhat less than 2.405 is chosen in practice in order to allow for manufacturing variations. One practical measure of single-mode operation is the cutoff wavelength, λ_c, above which the first higher-order mode is highly attenuated. Collectively, these constraints have led to typical values of $\Delta_T \leqslant 0.3$ percent and $d \geqslant 8.7$ μm for matched-cladding single-mode fiber products. There are two parameters that describe how well bound the fundamental mode is in the fiber: the V number and the mode field diameter (MFD). The V number describes the fraction of the optical power in the core; a higher V number means that more power is confined to the core. The MFD (the $1/e^2$ level of a Gaussian fit to the near field optical power) depends upon d and the V number and describes how concentrated the power is in the center of the fiber. The MFD is 9.6 μm when $\Delta_T = 0.30$ percent and $d = 8.7$ μm.

The depressed cladding design, by comparison, has two additional profile variables (Δ_D and D) which give more freedom in optimizing the lightguiding properties. The intrinsic scattering loss is kept low, as in the matched cladding design, by restricting the amount of germanium added to the core. However, the waveguide dispersion can be tuned by adjusting Δ_T through Δ_D. Most important of all, the high attenuation (cutoff) of the first higher-order mode is dominated by a leaky-mode mechanism in depressed-cladding designs[6-8] which depends on both the core and the depressed cladding. The leaky-mode loss results in λ_c of a depressed-cladding fiber being much shorter, by perhaps 100 nm, than λ_c of a matched-cladding design with the identical core parameters. Alternatively, the profile parameters of the depressed-cladding fiber can be selected so that the fiber is single-mode at $V > 2.405$. This results in tighter confinement of the fundamental mode to the core, and the proper combination of Δ_T and d can also result in a smaller MFD, concentrating the power in the center of the fiber. The nominal parameters for AT&T's depressed cladding design are $\Delta_T = 0.37$ percent, $d = 8.3$ μm, $\Delta_D = 0.12$ percent, and $D/d = 6.5$ which results in MFD $= 8.8$ μm.

Transmission properties. Magnified spectral loss and dispersion curves in the 1310-nm region for a typical AT&T production fiber are shown in Figure 5. The median loss at 1310 nm is 0.35 dB/km and at 1550 nm (not shown here) is 0.20 dB/km. Losses as low as 0.16 dB/km (with a median of 0.192 dB/km) at 1550 nm have been achieved in an experimental fiber design which minimizes Rayleigh scattering by producing a nearly pure silica core while further depressing the inner cladding index in order to achieve a lightguiding profile.[9] These loss values for MCVD fiber are equal to those reported for matched cladding fiber made by the major competitive preform fabrication processes, the

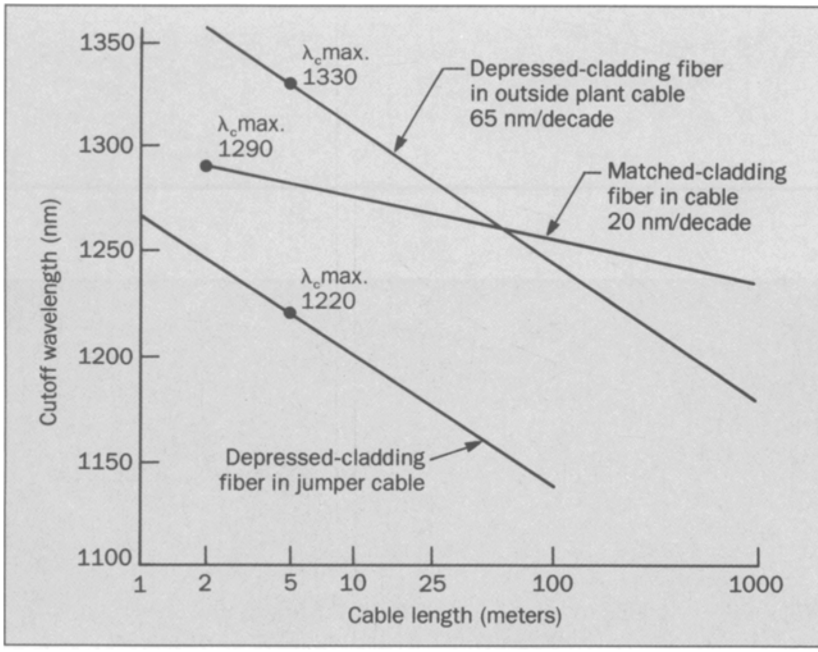


Figure 6. Cutoff wavelength versus fiber length for depressed-cladding and matched-cladding single-mode fibers.

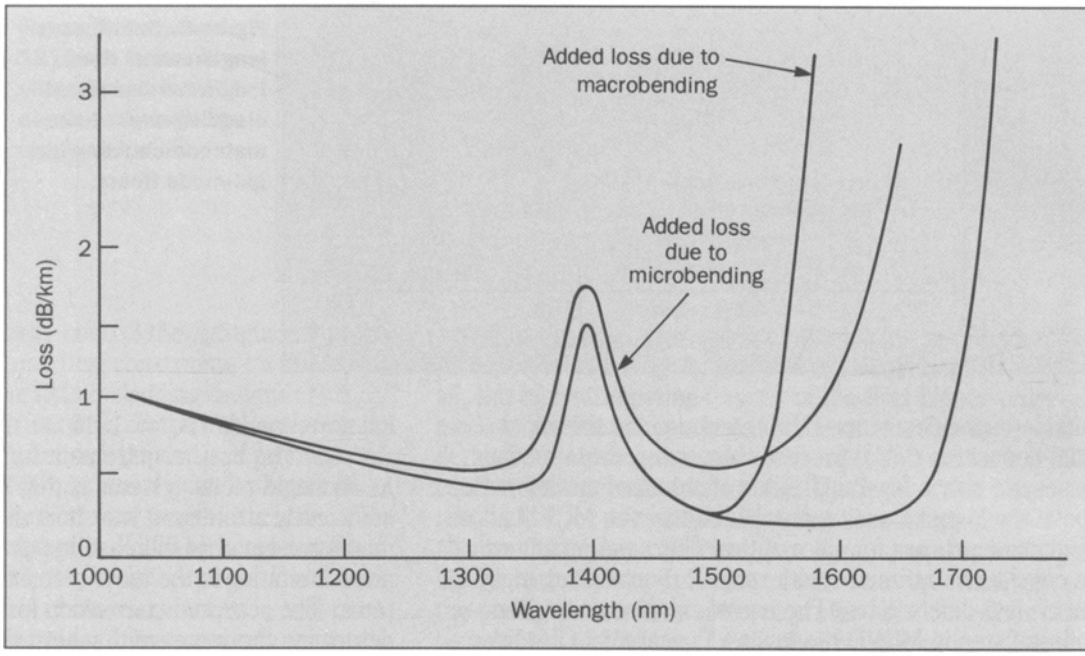
outside-vapor-deposition (OVD) process and the vapor-axial-deposition (VAD) process. Moreover, these median losses are only a few hundredths of a decibel per kilometer above the lowest losses reported, so that the MCVD production process for silica optical fibers essentially can be considered optimized with respect to producing high-purity, low-defect glass. The use of chlorine during the collapse step in MCVD produces a typical total OH absorption peak at 1390 nm of less than 1.5 dB/km. A low OH peak is important in order to have a small loss variation across the entire system wavelength window; the loss variation from 1285 to 1330 nm in Figure 5 is about 0.03 dB/km.

The slope of the dispersion curve in the vicinity of λ_0 is approximately 0.09 ps/nm^2-km for both the depressed- and matched-cladding fibers; this value is relatively insensitive to the normal fiber-to-fiber variations in composition and index profile. The dispersion slope is dominated by the material dispersion of silica because the low concentration of germanium in these fibers and the low slope of the waveguide dispersion, Figure 3a, curve 1, do not significantly alter the total dispersion slope. Consequently, the maximum dispersion over a system window, e.g., from 1285 to 1330 nm, is controlled by the variation in λ_0 from fiber-to-fiber profile variations that alter the magnitude of the waveguide dispersion. The specification limits in Figure 5 of dispersion ≤ 3.2 ps/nm-km correspond to $\lambda_0 = 1310 \pm 10$ nm.

The basic requirement for the cutoff wavelength, λ_c, in single-mode systems is that higher-order modes be sufficiently attenuated in a short distance in order to avoid modal noise and an increase in pulse dispersion. The modal noise limitation is the most restrictive for high-bit-rate systems. The accepted convention for measuring λ_c is to determine the wavelength where the difference in loss of the higher-order mode and the fundamental mode is about 20 dB in a given length of fiber. The choice of a test length is somewhat arbitrary; many manufacturers of matched-cladding fiber have used a 2-m length, while AT&T has used a 5-m length for the depressed-cladding design. The test procedure for λ_c implies that λ_c will be a function of length and indeed this has been demonstrated[10] as shown in Figure 6. The fact that no asymptotic value of λ_c is observed, at least to 1 km, means that the loss of the higher-order mode is higher than that of the fundamental mode even to wavelengths well below 1310 nm. Conversely, at any wavelength, there will be a fiber length where the fraction of power in the higher-order mode becomes negligible so that there is no modal noise and no additional pulse broadening.

The two different slopes in Figure 6 reflect the different mechanisms for loss of the higher-order mode in the depressed- and matched-cladding designs, with the cutoff of the depressed cladding fiber decreasing more rap-

Figure 7. Schematic single-mode fiber spectral loss curves with added macro-bending loss and added microbending loss superimposed.



idly with length. It is clear that the same requirement for cutoff wavelength cannot be applied to both types of fiber because the measured λ_c depends on the test length. In the example shown, the curves are pinned by the maximum λ_c normally specified for each fiber; 1290 nm in 2 m for the matched cladding and 1330 nm in 5 m for the depressed cladding. The 1290-nm maximum for the matched-cladding fiber evolved by convention without specific transmission limits being determined. The 1330-nm maximum for the depressed-cladding fiber was established by experiments and modeling of modal noise as a function of laser characteristics, fiber length between splices, and splice losses[11] and gives a very conservative bound for avoiding modal noise in 1310-nm systems. For example, essentially no noise penalty would occur at 1285 nm for any cable length greater than 10 m between two high-loss splices when λ_c = 1330 nm (in 5 m) for the depressed-cladding fiber. Since outside plant cable lengths will always be greater than 10 m, even for short-length repairs, the 1330-nm cutoff wavelength poses no problem. Selected fibers with λ_c values below 1220 nm (in 5 m) are used for short-length jumpers and component fibers so that modal noise is avoided in very short lengths.

Mode field diameter. There are three sources of added loss in a cable path that depend upon the mode field diameter: splice loss, macrobending loss, and microbending loss. The splice loss increases very gradually as the mode field diameter decreases while the two bending-induced losses decrease very rapidly as the mode field diameter decreases. The depressed cladding design concept takes advantage of these functional dependencies by working at a mode field diameter where there is a much higher resistance to bending-induced losses than for the common matched-cladding fiber, but with no significant increase in joining loss.

The splice loss effect arises from an offset

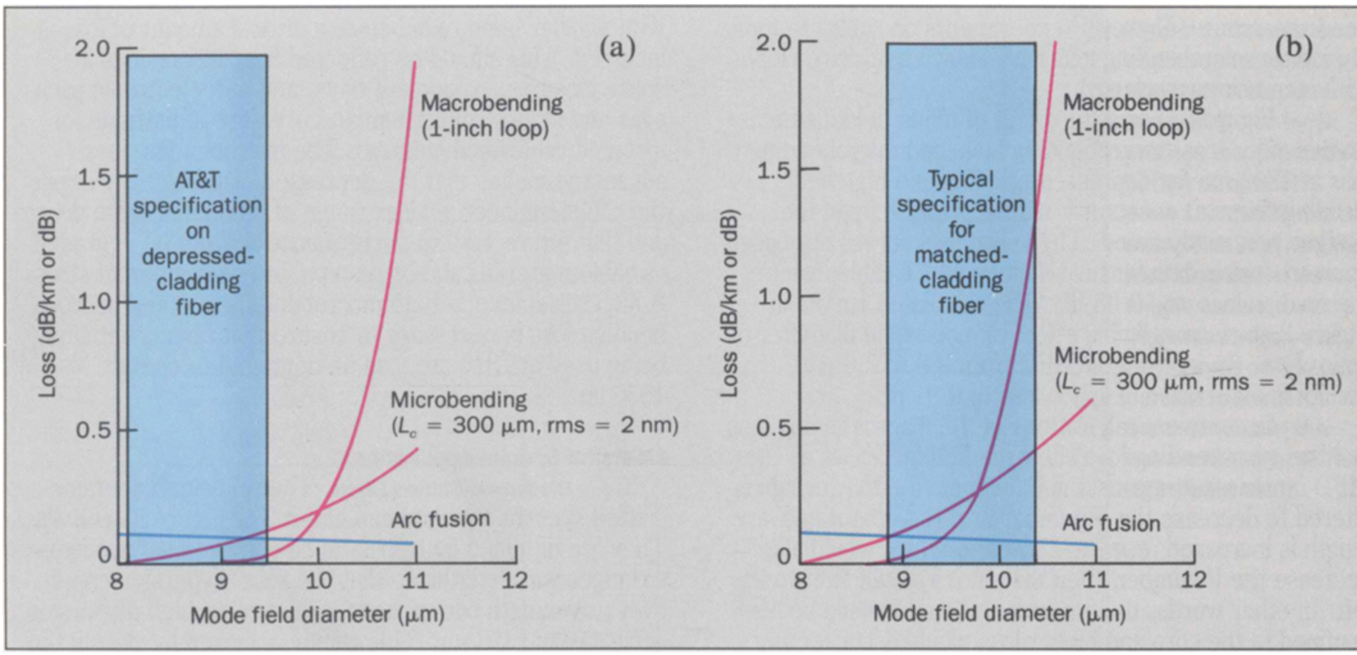


Figure 8. Calculated added loss from splicing, macrobending, and microbending, each as a function of mode field diameter for: (a) depressed-cladding fiber (V = 2.514) and (b) matched-cladding fiber (V= 2.373). Wavelength is 1310 nm.

between the optical power fields[12] due to such factors as eccentricity of the fiber core, outside diameter mismatch, or misalignment due to the splicing technique.

The macrobending loss effect is due to optical power locally radiating out of the fiber at bends of loops in the fiber axis[6] that are large with respect to the fiber diameter, e.g., radii of the order of several millimeters or more. Fiber bends are typically found in splice cases where loops of accumulated fiber are stored, on equipment racks where fibers are interconnected or terminated, and exiting from optoelectronic packages. A single turn of fiber could cause a significant loss of power depending on the radius of curvature, the wavelength, and the fiber design.

Microbending refers to deflections of the fiber axis that are small compared to the fiber diameter and which are randomly distributed along the fiber length with spacings of the order of the fiber diameter. Microbending loss occurs because of power continually radiating out of the fiber along its length.[13] Microbends can arise from a variety of factors such as small variations in the fiber, coating, or cable dimensions, or from cable deformation during plowing or pulling into ducts, or from the various cable materials contracting different amounts during normal seasonal changes in the temperature.

The effect of macrobending and microbending on the shape of the spectral loss curve is shown in Figure 7. Macrobending causes a sharp increase in loss; this loss edge moves to shorter wavelengths as the bend radius decreases.[6] The microbending spectral dependence can have a negative, zero, or positive slope depending upon the bend spectrum.[13] However, experiments on cables to forcibly induce microbending loss have shown a positive slope with increasing wavelength.

Figure 8 shows the effect of mode field diameter on the splice loss, macrobending loss, and microbending loss at 1310 nm for depressed-cladding and matched-cladding fibers at constant *V* numbers based upon the designs previously noted. The splice loss curves are based upon arc fusion data for field-spliced AT&T cables where the median loss was 0.08 dB. The calculated curves in Figure 8 show a negligible effect of mode field diameter on splice loss. An increase in MFD from 8.8 to 9.6 μm results in a decrease in splice loss of 0.01 dB.

In contrast, calculations of the macrobending loss and the microbending loss show marked increases as the MFD increases at a constant *V* number. If either design is altered to decrease the *V* number or if the operating wavelength is increased, e.g., to 1550 nm, which would also decrease the *V* number, then the curves would shift to the left. In other words, the fundamental mode would be less confined to the core and higher loss would occur for any mode size. The 1-inch loop diameter for the macrobending calculation[6] was arbitrarily chosen for illustrative purposes; as the loop diameter increases the macrobending curve would shift to the right. The 300-nm correlation length (L_c) and 2-nm rms deformation amplitude for the microbending calculation[13] were selected on the basis of laboratory cable tests.

The indicated specification ranges for MFD overlaid on the splice and bending loss curves illustrate the essential advantage of the depressed-cladding design; the fiber operates at a higher *V* number and a lower mode size where bending-induced losses are negligible compared to the matched-cladding design under the same bending conditions. The conclusions from these analyses have been confirmed by an extensive experimental comparison of the susceptibility to bending-induced losses of the AT&T depressed-cladding fiber and a common matched cladding fiber.[14] The macrobending loss advantage means that the depressed cladding fiber can be used in physical designs with smaller bend radii before a critical amount of loss is incurred. This should be reflected in space savings in splice closures, equipment bays, and optoelectronic packages and in less concern about curvature limitations for installed cables and jumpers. The microbending loss advantage means that the depressed-cladding fiber offers the cable engineer a wider range of options in cable design and that future system performance will not be degraded as cable materials age or respond to environmental stress. A high resistance to both macrobending loss and microbending loss is necessary to ensure that fibers, initially being used at 1310 nm, can be upgraded to operate also at 1550 nm.

Fibers for Special Applications

Dispersion-Shifted Fibers. The relevant dispersion-shifted spectra are shown in curve 2 of Figure 3a and 3b. They are obtained by translating a conventional spectrum to longer wavelengths so that the zero dispersion crossover wavelength occurs near 1550 nm but high dispersion occurs near 1310 nm. This can be achieved by raising the index across a smaller diameter core, or equivalently by grading the index across the core with a profile shape like a triangle.[15,16]

Figure 9a plots mode power versus radius and shows that the triangular gradient forms a self-focusing profile which confines the propagating beam to a smaller spot inside the core than a corresponding step-index profile would. Since waveguide dispersion becomes larger as the spot size becomes smaller, it is clear that a triangular graded-index fiber can have a larger core diameter than a step-index fiber and still produce the same magnitude of waveguide dispersion. Figure 9b plots the wavelength of zero dispersion as a function of core diameter in micrometers and shows that triangular fiber profiles can have larger diameters than equivalent step-index fibers and still achieve zero dispersion near 1550 nm. Since the curves go through maxima, the choice for the peak index to the apex of the triangle can be chosen to minimize dimensional tolerance requirements by making the curve just tangent to

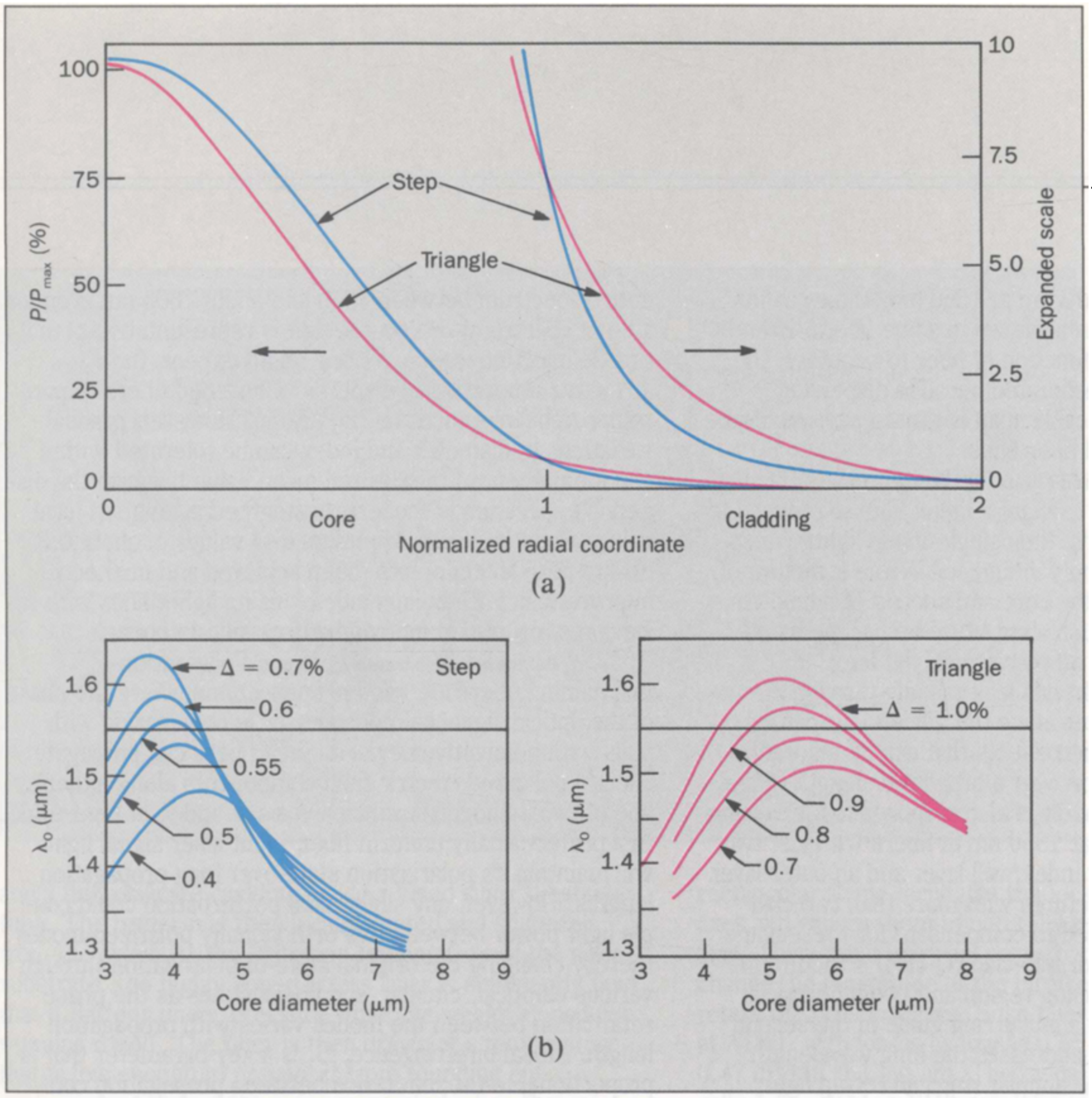


Figure 9. Comparison of dispersion-shifted fibers with step-index and triangular-index profiles for: (a) distribution of optical power versus distance from fiber axis and (b) zero dispersion wavelength versus core diameter. In (a), the two curves on the left pertain to the left-hand scale and the two on the right to the right-hand scale.

λ_0 = 1550 nm. That defines a minimum Δ_T necessary to achieve λ_0 = 1550 nm. However, the need to minimize extrinsic bending effects makes it imperative to optimize mode confinement characteristics by operating at as high a V number as possible. Therefore, the region to the right of the design peak is the best operational choice. For the triangular core design, it corresponds to 0.8 percent $< \Delta_T <$ 1.0 percent and $0.5 < \lambda_c/\lambda < 0.6$. The triangular profile shape also provides the added benefit of having a smoother and less abrupt interface between the cladding and the higher index core region which has resulted in lower losses than for equivalent step-index profiles.

Intrinsic fiber losses can be reduced by lowering the germanium core dopant concentration and using fluorine to depress the cladding index in order to maintain the same Δ_T. Since dispersion-shifted lightguides are relatively weakly guiding, they require thick deposited claddings to prevent a significant fraction of the total power, P, from either traveling in the high-loss substrate cladding or leaking through its interface with the depressed-index region. For example, if $\Delta_D = -0.1$ percent, then the D/d ratio must be greater than 7 in order to keep the added losses low at 1550 nm. Dispersion-shifted fibers with depressed-index claddings are currently being fabricated with average losses of less than 0.25 dB/km at 1550 nm. Values as low as 0.20 dB/km have been achieved in some fibers. Even though λ_0 is a sensitive function of fiber parameters, the tolerance problem is ameliorated because dispersion through a concatenated cable span is the length-weighted average of the individual fiber links.

Dispersion-Flattened Fibers. If the depressed cladding width of a step index or triangular index fiber is reduced to about the size of the core, then single-mode lightguiding properties become strongly influenced by the structure of the index well between the core and second cladding. An important property of such a structure is that the fundamental mode can be cut off more readily at long wavelengths because light can leak radially through the index well as it propagates along the guide. This causes large waveguide dispersion effects that can be tailored to cancel material dispersion over a broad wavelength range. However, the same property is also responsible for causing relatively high losses near 1550 nm in fibers with just two cladding layers, an inner index well layer and an outer layer.

Lightguide structures with more than two claddings have been conceived to compensate for the leakage loss problem.[17] The quadruple-clad (Q-clad) structure in Figure 1d has a core-guiding region and two index wells that are separated by an annular ring guide in the second cladding. This structure addresses the long wavelength loss problem because the annular ring can retrap light which leaks through the inner index well. The Q-clad fiber has eight independent radial and index parameters that can be optimized to achieve low loss and low dispersion. In particular, the core and inner index well can be used to control low dispersion while the remaining second, third, and fourth claddings can be used to maintain low losses at long wavelengths. Curves 3 in Figure 3a and 3b show dispersion results for dispersion-flattened fibers with less than 2 ps/km-nm everywhere between zero crossings near 1310 and 1550 nm.

This corresponds to bandwidth peaks which are higher than 1000 GHz-km near the minimum dispersion wavelengths and remain higher than 50 GHz-km across the entire spectrum between 1310 and about 1600 nm even for a 2-nm spectral width source that is representative of multimode injection lasers. As one might expect, the attractive properties of dispersion-flattened fibers require rather tight tolerances on the profile. However, gradual variations of diameter and index can be tolerated within about 5 percent of the desired mean value because the dispersion spectrum is the length-weighted average of local values along the fiber. Minimum loss values of about 0.3 dB/km near 1520 nm have been achieved and further improvements are being made by using lightguides with silica cores, or graded-index germania-silicate cores.

Polarization-Maintaining Fibers. Polarization-maintaining fibers are used in applications where the phase of the optical signal is important, or in conjunction with polarization-sensitive devices. Such fibers can propagate linearly polarized electric field components along either one of two orthogonal principal axes, x and y, in Figure 10. In a perfect axially uniform fiber, input laser signal light will maintain its polarization state over long propagation lengths. However, any slight axial perturbation could couple light power between two orthogonally polarized modes thereby changing the original state of polarization through various elliptical, circular, and linear states as the phase retardation between the modes varies with propagation length. Modal birefringence, B, is a key parameter that is proportional to the difference between propagation constants β_x and β_y, along orthogonal principal axes.

A large value of B is required in order to maintain polarization over long propagation lengths. The difference between β_x and β_y can be accentuated by fabricating lightguides either with asymmetric profile shapes within elliptical cores or with anisotropic index distributions around circular cores.[18,19]

The MCVD processing technology is being used to stress-induce high birefringence into single-mode fibers with elliptical cladding regions as illustrated in Figure 10. First, a circular preform is fabricated by depositing a germania-silicate core, a fluorosilicate buffer cladding region, a germania-borosilicate stress-producing cladding region,

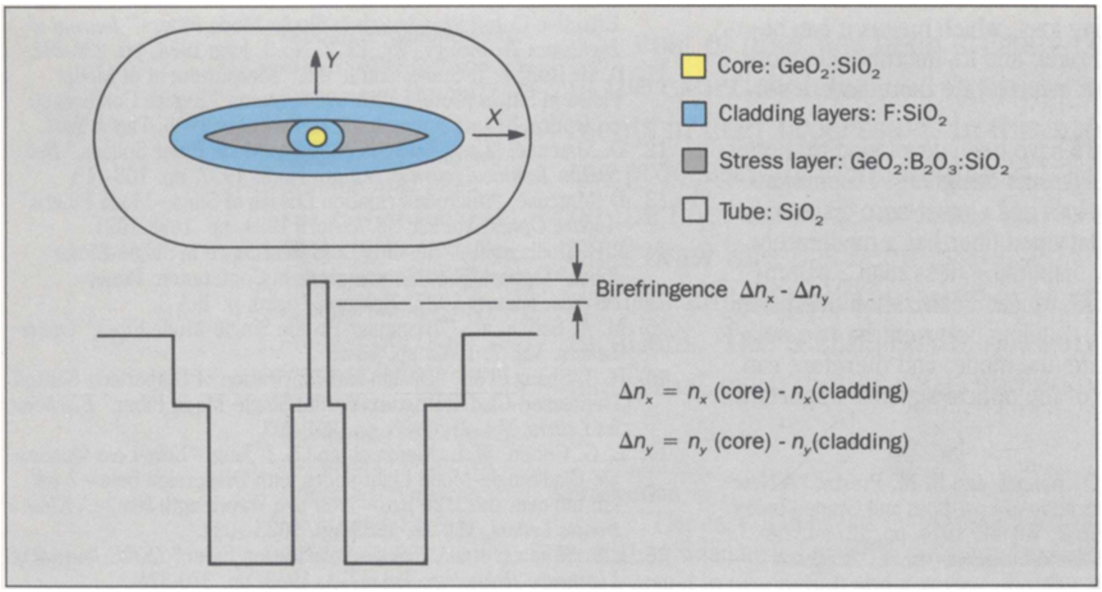


Figure 10. Polarization-maintaining fiber cross section showing sequence of various composition layers and refractive-index profile.

and a fluorosilicate cladding inside a fused silica substrate tube. The preform is then locally heated and squeezed from the sides. At the softening temperature of the silica substrate, the highly doped stress layer is sufficiently fluid that it flattens under pressure while the weakly doped core remains round. The fiber is then drawn at a temperature that is low enough to prevent it from rounding out.

Anisotropic stresses are created when the preform is drawn into fiber because the borosilicate cladding layer has a larger coefficient of thermal expansion which makes it shrink faster than the relatively stiff central core. As a result, the core is highly stressed along the major x axis of the elliptical cladding. The refractive-index profiles, for x axis and y axis orientations, are very reminiscent of those shown in Figure 1d because the borosilicate cladding region forms a deep index well between fluorosilicate cladding regions on either side. However, the fiber has relatively high birefringence because the high stresses on the core cause Δn_x to be slightly larger than Δn_y.

An important feature of these fibers is that their rectangular shape facilitates the location of their principal axes and causes them to naturally bend along the major axis. Thus, most external perturbations should only change the magnitude of the birefringence rather than rotate the principal axes. Such fibers have been fabricated, at AT&T, with losses as low as 0.56 dB/km at 1310 nm and 0.47 dB/km at 1550 nm. The modal birefringence is typically 1.6×10^{-4} at 1310 nm. The extinction ratio, between one linearly polarized mode and an orthogonally polarized mode, is very low (-45 dB after 5 m, and -23 dB after a 1-km propagation length).

Conclusions

AT&T depressed-cladding single-mode fiber is tailored for 1310-nm systems but also has capability to support systems in the 1550-nm window. The MCVD process for producing this fiber has been optimized with respect to reproducibly obtaining low loss at both 1310 and 1550 nm and almost zero dispersion at 1310 nm. The essential advantages of this fiber design are its superior resistance to macrobending loss, which means it can be deployed with small bend radii, and its microbending loss resistance, which means it can tolerate more severe service environments.

Three other fibers have been developed that offer interesting properties to systems designers. Dispersion-shifted fiber provides low loss and almost zero dispersion at 1550 nm. Dispersion-flattened fiber has a moderately low loss and provides low dispersion (less than 2 ps/nm-km) over a wide wavelength range. Polarization-preserving fiber maintains low power coupling between the two polarization states of the fundamental mode, and therefore can be used where the phase of the optical signal is important.

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