Radiating Leaky-Mode Losses in Single-Mode Lightguides with Depressed-Index Claddings

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Abstract—Cutoff characteristics are calculated for the fundamental mode in a single-mode double-clad lightguide structure whose refractive index in the inner cladding is less than the index of the outer cladding. Results of this study indicate how to choose the proper depressed cladding width and depth in order to reduce long-wavelength losses that have been observed in experimental MCVD fibers with fluorine-doped phosphosilicate claddings.

I. Introduction

IN order to be suitable for long-distance transmission, a single-mode lightwave cable should have low Rayleigh scattering losses, low bending-induced losses, and minimum chromatic dispersion near the system operating wavelengths.

Fig. 1(a)-(d) compares refractive index profile shapes for four types of single-mode lightguides. The type in Fig. 1(a) is most often described in the literature [1]. It typically has a germania-silicate deposited core and a germania-phosphosilicate deposited cladding whose refractive index $n_o(1 + \Delta)$ is slightly larger than the index n_o of silica. A small amount of fluorine is sometimes added in the cladding to compensate for phosphorous and achieve $\Delta' = 0$. Fig. 1(b)-(d) illustrates profile structures characteristic of double-clad fibers [2] in which fluorine is deposited within an inner cladding to depress its refractive index ($\Delta' < 0$) below that of an undoped silica outer cladding [3]-[6]. The cores of these fibers can contain germania-doped silica as in Fig. 1(b) or phosphosilicate as in Fig. 1(c). Double-clad fibers with wide depressed claddings approximate step-index fibers with infinite claddings. However, if the depressed cladding width is reduced, as in Fig. 1(d), then single-mode lightguiding properties become influenced by Δ' as well as by Δ. Such lightguides are potentially useful for wavelength-division-multiplexing applications because they can be tailored to have low dispersion between two zero dispersion wavelengths [7]-[10].

Experimental studies have indicated that lightguide structures, typified by Fig. 1(a), with 110 μm OD, 7.5 μm core diameter, and $\Delta = 0.5$ percent provide very low loss and very good resistance to bending-induced loss (cabling loss) [11]. However, they have minimum dispersion near λ_o = 1.35 μm which is too far removed from system operating wavelengths near 1.30 μm [12]. Germania-fluoro-phosphosilicate depressed-index-cladding lightguides are attractive alternative structures because the germania dopant increases the material refractive index and the zero-material-dispersion wavelength ($\lambda_o > 1.28$ μm) while fluorine dopant decreases those same parameters. As a result, the two dopant material contributions can be counterbalanced and the total chromatic dispersion in such fibers can be minimized at any desired wavelength, in the range $1.28 < \lambda < 1.38$ μm, for any fiber core diameter ranging between 6 and 10 μm [13]. Therefore, fiber waveguide parameters, like core diameter and index difference, can be chosen to minimize bending-related losses while dispersion effects can be minimized by choosing the proper material concentrations.

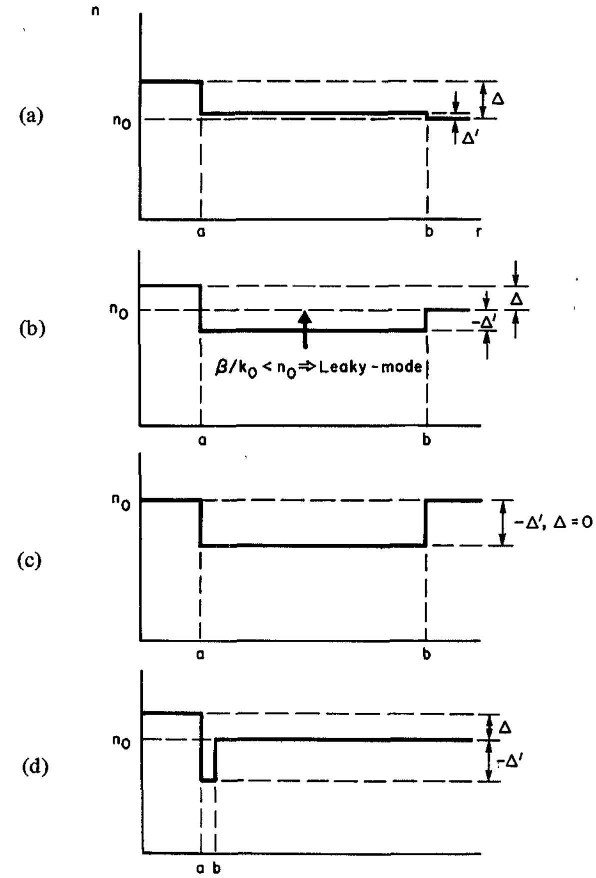

Fig. 1. Refractive index profile shapes for four types of single-mode lightguides.

However, one disadvantage of depressed-index-cladding lightguides is that they have been observed to have high losses at long wavelengths [3]-[6]. The purpose of this paper is first, to describe the leaky mode mechanism which is responsible for radiative losses of the fundamental mode, and second,

Manuscript received February 2, 1982; revised June 6, 1982.
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0018-9480/82/1000-1455$00.75

to provide guidelines for ensuring low losses in future double-clad fibers.

Central to the discussion of radiative mode losses in this paper is the notion of cutoff of the HE_{11} mode. Since this term may easily be misunderstood, a brief definition is given below. A mode is said to be guided when its field outside of the fiber core decays exponentially as a function of the radial coordinate. On the other hand, the modal field can sometimes form a radial traveling wave in the outer cladding after an initial exponential decay near the fiber core. If this happens, then the mode is said to be cutoff. Thus, the term "cutoff" does not imply that power cannot be transmitted along the fiber. It simply means that because the power is not totally trapped inside the fiber core, some power can leak out and be lost by the process of radiation. Thus, cutoff occurs whenever the mode field assumes a radiative character at a large radial distance from the fiber core.

Section II describes cutoff conditions for the fundamental mode in double-clad fibers, typified by Fig. 1(b)-(d). Section III describes leakage losses in fibers, typified by Fig. 1(b) and (c), whose inner cladding thickness is much wider than the core radius ($b/a > 4$). Effects of constant curvature axial bends are included in Section III.

II. Cutoff Characteristics of Double-Clad Lightguides

Light guiding properties of enhanced-index cladding structures [Fig. 1(a)] are fundamentally different from properties of depressed-index cladding structures [Fig. 1(b)-(d)] at long wavelengths. The fundamental HE_{11} mode in a step-index fiber with $\Delta' \geqslant 0$ [Fig. 1(a)] does not become cutoff even at an arbitrarily long wavelength. However, a wide deposited cladding (with constant refractive index) is still required because waveguide imperfections like bends and lossy outer fused silica cladding tubes cause high losses if the fundamental mode field penetrates deep into the outer cladding. By comparison, if $\Delta' < 0$ [Fig. 1(b)-(d)], then the HE_{11} mode can become cutoff, even in a perfect lightguide, if the effective modal phase-index becomes smaller than the index of the outer cladding. Therefore, the wavelength at cutoff depends on the ratio of the modal propagation constant β to the propagation constant $k = 2\pi/\lambda$ of a plane wave in free space.

If $\beta/k > n_o$, then there are no leakage losses. However, if the propagation constant is smaller, so that $\beta/k < n_o$ as shown in Fig. 1(b), then the mode is said to be "cutoff" because power radiates through the outer cladding. Notice that if $\Delta = 0$, as in Fig. 1(c), then $\beta/k < n_o$ and there are leakage losses at all wavelengths. This does not preclude using the fiber for long-distance communications because the fundamental mode leakage loss can be made arbitrarily small if the depressed cladding is made sufficiently thick. For example, if the cladding is made wide enough, then the mode amplitude will decay to a negligibly small value at the outer diameter of the index well from where the mode leaks.

Propagation characteristics of straight double-clad lightguides are determined from the eigenvalue equation for the weakly guiding approximation [2]. Axial curvature effects will be considered in Section III for the limit $b/a \gg 1$

$$\begin{aligned}&[\gamma J_o(\kappa a) I_1(\gamma a) + \kappa J_1(\kappa a) I_o(\gamma a)]\\ &\quad \times [\delta K_o(\gamma b) K_1(\delta b) - \gamma K_1(\gamma b) K_o(\delta b)]\\ &\quad + [\gamma J_o(\kappa a) K_1(\gamma a) - \kappa J_1(\kappa a) K_o(\gamma a)]\\ &\quad \times [\delta I_o(\gamma b) K_1(\delta b) + \gamma I_1(\gamma b) K_o(\delta b)] = 0. \qquad (1)\end{aligned}$$

The terms in (1) include quantities defined in (2) as well as K_1, modified Hankel functions and J_ν and I_ν, Bessel and modified Bessel functions of order ν and $\delta = -i\sigma = (\beta^2 - n_o^2\kappa^2)^{1/2}$

$$\left.\begin{aligned}\kappa &= [n_o^2(1+\Delta)^2 k^2 - \beta^2]^{1/2}\\ \gamma &= (\beta^2 - n_o^2(1+\Delta')^2 k^2)^{1/2}\\ \sigma &= (n_o^2 k^2 - \beta^2)^{1/2}\\ \Delta &= [n(\text{core}) - n(\text{outer clad})]/n_o\\ \Delta' &= [n(\text{inner clad}) - n(\text{outer clad})]/n_o\end{aligned}\right\}. \qquad (2)$$

The eigenvalue (1) can be used to derive the cutoff condition for the modes of the double-clad fiber. Since cutoff occurs when $\sigma = 0$, because the phase-index of a mode becomes less than the index of the outer cladding, it is useful to define a cutoff V_c number which depends on Δ, a, and the cutoff wavelength λ_c through

$$(\kappa a)^2 = V_c^2 = \left(2\pi \frac{a n_o}{\lambda_c}\right)^2 (2\Delta). \qquad (3)$$

By taking the proper limits, (1) reduces to the cutoff condition

$$\begin{aligned}&\gamma J_o(\kappa a) [I_1(\gamma a) K_1(\gamma b) - K_1(\gamma a) I_1(\gamma b)]\\ &\quad + \kappa J_1(\kappa a) [I_o(\gamma a) K_1(\gamma b) + K_o(\gamma a) I_1(\gamma b)] = 0 \qquad (4)\end{aligned}$$

which can be used to compute V_c.

Fig. 2 summarizes the cutoff behavior for the fundamental mode of the double-clad fiber. The solid curves show the cutoff value V_c as a function of the cladding radius ratio b/a for several values of the refractive index parameters $H = -\Delta/\Delta'$. A truly guided mode exists only in the region above a given curve while the area below the curves indicates the region where the HE_{11} mode is cutoff because of leakage losses. No cutoff occurs if $V_c = 0$, as in the limit $b/a \to 1$, which applies to ordinary step-index fibers.

However, the solid curves in Fig. 2 do not tell the whole story since they were derived under the assumption that the fiber has an infinitely extended outer cladding. Near cutoff the field reaches deep into the outer cladding where material losses are much larger than in the inner deposited cladding. As a result, fiber losses begin to increase at a shorter wavelength than the mathematical cutoff. The effect is illustrated in the inset which plots the normalized mode power P/P_{tot} as a function of normalized radius r/a. The lightguide parameters $H = 2$ and $b/a = 1.43$ correspond to the intersection of the dashed lines in the figure. Mathematical cutoff occurs at $V_c \sim 1.6$ ($\lambda_c \sim 1.744$ μm if $a = 5$ μm, $\Delta = 0.2$ percent). Low losses should be maintained as long as the wavelength is below cutoff and most of the propagating power remains confined within the core and inner cladding. Curves (a)-(d) in the inset correspond to $V_1 = \kappa a n_o [2\Delta]^{1/2} = 1.88$, 1.73, 1.62, and 1.61 for which the fraction of confined power is 92, 75, 13, and 9

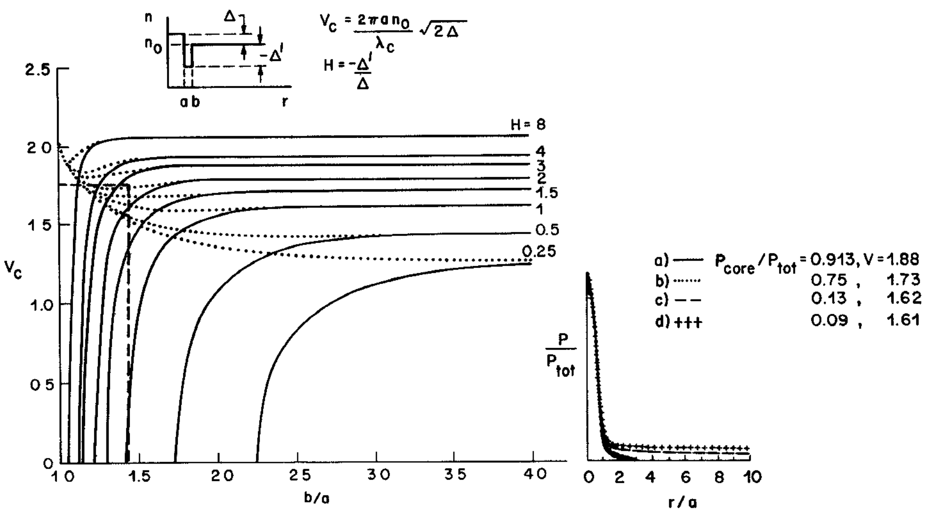

Fig. 2. Cutoff characteristics for index profiles like Fig. 1(b) and (d). The V_1 number ($V_c = (2\pi a/\lambda_c)\, n_o\sqrt{2\Delta}$) at cutoff is plotted versus b/a. The curves apply to different values of $H = -\Delta'/\Delta$ ($0.25 \leqslant H \leqslant 8$). Leakage losses remain low in the region above individual curves for constant H. Solid curves represent mathematically correct cutoff conditions which apply if the outer cladding is infinitely thick and composed of perfect fused silica material. The dotted curves represent more practical conditions which assume cutoff if more than 25 percent of the mode power propagates outside the fiber core. An inset curve plots normalized mode power P/P_{tot} versus r/a for the specific case ($H = 2$, $b/a = 1.43$, $a = 5$ μm) indicated by dashed lines on the cutoff characteristics. Curves a-d apply to several V_1 numbers close to cutoff.

percent, respectively. The smallest practical V_1 number that can maintain low loss is $V_1 \sim 1.73$ ($\lambda \sim 1.63$ μm if $a = 5$ mm, $\Delta = 0.2$ percent) since power in the outer cladding becomes excessively large for smaller V_1 values.

With that in mind, a more practical cutoff condition was used to calculate the dotted curves in Fig. 2. Instead of requiring cutoff in the sense of letting $\sigma \rightarrow 0$ or $\beta \rightarrow n_o\kappa$, the dotted curves were computed by requiring that 75 percent of the power of the HE_{11} mode be carried inside of the region of the fiber from $r = 0$ to $r = b$. It is clear that this "practical cutoff" condition results in curves that can be quite different from the ideal mathematical cutoff indicated by the solid curves. At one extreme, when $b/a \rightarrow 1$, the inner cladding disappears and the dotted curves approach the V number ($V_c \approx 2.03$) at which 25 percent of the power propagates in the cladding of a step-index fiber. At the other extreme, when $b/a \rightarrow 4$, the dotted curves asymptotically approach mathematical cutoff limits set by the solid curves.

III. Fundamental Mode Leakage Loss in Lightguides with Wide Depressed-Index Claddings

This section describes how to estimate radiative leakage losses in double-clad lightguides with wide depressed-index claddings [$b/a > 4$ as in Fig. 1(b) and (c)]. Effects of constant curvature bends are included since they can cause leakage losses even if $\Delta > 0$ and $\beta/k > n_o$. A bent lightguide can be represented by an equivalent straight lightguide whose effective refractive-index profile n_{eff} is deformed as indicated in (5) [14]

$$n_{\text{eff}} = n(r)\left[1 + \frac{r}{R}\cos\phi\right] \tag{5}$$

where R is the radius of curvature of the bent fiber axis, $n(r)$ is the refractive index of the straight fiber, and r and ϕ are the radial and azimuthal coordinates of a cylindrical polar coordinate system with $\phi = 0$ in the plane of the curved fiber. The worst case occurs in the plane of curvature where

$$n_{\text{eff}} = n(r)\left[1 + \frac{r}{R}\right] \tag{6}$$

as illustrated in Fig. 3. The radius of curvature that makes $n_{\text{eff}} = \beta/k$ at $r = b$ is given by

$$R = \frac{bn_o}{\beta/k - n_o}. \tag{7}$$

If, for example, $(\beta/k - n_o)/n_o = 0.1$ percent in a straight fiber, the guided mode field would turn into a radiating field at $r = b$ when the radius of curvature reaches the value $R = b \times 10^3 (b)$ which could be on the order of 50–100 mm.

Thus, even if $\beta/k > n_o$ in the straight fiber shown in Fig. 1(b), a bend can deform the refractive index profile so that $\beta/k < n_{\text{eff}}$ as shown in Fig. 3. For this reason it is desirable to make b/a large enough to ensure tolerable leakage losses even if $\Delta = 0$ because this case may arise unintentionally when the fiber is bent.

An approximate formula for radiation losses in double-clad fibers with wide depressed cladding can be derived in the following way. Begin by considering a step-index profile with either $b \rightarrow \infty$ or $\Delta' = 0$. The electromagnetic field solution computed for the step-index fiber is then used as a zero-order approximation for calculating radiation losses of the double-clad fiber. This is done by introducing a reflected wave at the index step $r = b$ and a transmitted wave in the outer cladding at $r = b$. The corresponding wave amplitudes are found by requiring that boundary conditions be satisfied at $r = b$ with the zero-order field solution being regarded as an "incident" wave on the index step at $r = b$. The power loss coefficient 2α can then be computed from the power that is radiated radially per unit length of fiber, divided by the power

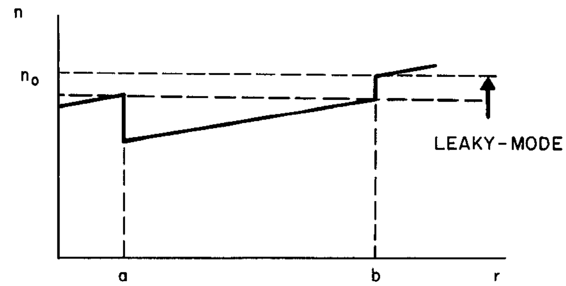

Fig. 3. The effective refractive index profile, in the plane of curvature of a bent fiber, shows how an actual profile like Fig. 1(b) would be distorted by a bend.

carried by the guided mode along the fiber axis. For the straight fiber we thus obtain the loss formula

$$2\alpha = \frac{2\pi\kappa^2\gamma\sigma e^{-2\gamma b}}{\beta n_o^2\kappa^2|\Delta'|V_2^2K_1^2(\gamma a)} \tag{8}$$

where

$$V_2 = kan_o(2(\Delta - \Delta'))^{1/2} = [(\kappa a)^2 + (\gamma a)^2]^{1/2}.$$

For curved fibers this procedure can be carried one step further. Instead of solutions of the straight fiber, we use simplified WKB-type solutions of the curved structure in the derivation sketched above. In this way the following formula for the loss of the curved double-clad fiber has been derived [15].

$$2\alpha(R) = \frac{4b\kappa^2}{\beta V_2^2K_1^2(\gamma a)}\int_0^\pi \frac{\bar{\sigma}(b)\,\bar{\gamma}^2(b)\,e^{-2u}}{u[\bar{\gamma}^2(b)+\bar{\sigma}^2(b)]}\,d\phi \tag{9}$$

with

$$\bar{\gamma}^2(r) = \beta^2 - n_o^2(1+\Delta')^2\left(1 + 2\frac{r}{R}\cos\phi\right)k^2 \tag{10}$$

$$\bar{\sigma}^2(r) = n_o^2\left(1 + \frac{2r}{R}\cos\phi\right)k^2 - \beta^2 \tag{11}$$

and

$$u = \frac{R[\gamma^3 - \bar{\gamma}^3(b)]}{3n_o^2(1+\Delta')^2k^2\cos\phi} \quad \text{for} \quad \phi \neq \frac{\pi}{2}$$

$$u = \gamma b \quad \text{for} \quad \phi = \frac{\pi}{2}. \tag{12}$$

For $R \to \infty$, (9) becomes identical with (8). However, (9) is applicable only as long as the effective refractive index β/k lies inside the range delineated by the two horizontal broken lines in Fig. 3. When the effective refractive index of the guided mode lies below the lower of the two broken lines, the following formula for a curved step-index fiber must be used [16]:

$$2\alpha = \frac{\pi^{1/2}\kappa^2\exp\left[-\frac{2}{3}(\gamma^3/\beta^2)R\right]}{2V_2^2\gamma^{3/2}R^{1/2}k_1^2(\gamma a)}. \tag{13}$$

When β/k above the upper broken line Fig. 3, a formula similar to (13) can be used, where the radial decay parameter for the inner cladding γ (appearing in the exponent of the exponential function) must be replaced by the corresponding radial decay parameter for the outer cladding.

Because (9) and (13) are only approximations, loss curves computed from these formulas do not necessarily join smoothly at the boundaries of their respective domains of applicability. However, possible discontinuities can usually be bridged by drawing a judiciously estimated smooth curve connecting the various branches.

Fig. 4 shows radiative leakage losses calculated as a function of wavelength for specific examples of straight lightguides simulating Fig. 1(b) with $\Delta - \Delta' = 0.5$ percent, $a = 3.75$ μm, and the positive index Δ as a variable parameter. The steep rise of the loss coefficient 2 α occurs near the HE_{11} mode cutoff wavelength λ_{co} at which $\beta/k = n_o$. The slopes of experimental loss spectra with respect to wavelength have been found to be in good agreement with the predicted curves in Fig. 4. This gives added credence to the leaky-mode loss mechanism described in this paper. Notice that λ_{co} becomes shorter as the index depression $-\Delta'$ becomes deeper relative to Δ. For example, if $b/a = 6$, then leaky-mode losses become greater than 0.1 dB/km for wavelengths longer than 1.38 μm if $-\Delta'/\Delta = 0$, or for $\lambda > 1.51$ μm if $\Delta = 0.25$ percent.

One of the critical controlling parameters on loss performance is the ratio b/a of the outer diameter of the deposited cladding relative to the core diameter. The effect of increasing b/a by depositing a thicker cladding can be appreciated by comparing the solid curves for $b/a = 6$ with the dashed curves for $b/a = 7$. Increasing b/a reduces the slope of the leakage loss curves and, as a result, increases the wavelength at which radiation losses become significantly greater than 0.1 dB/km. Notice that if $\Delta > 0.25$ percent, then radiation losses in Fig. 4 appear to be insignificant for wavelengths shorter than 1.6 μm.

However, the predicted losses for a straight fiber could be significantly increased due to bending effects induced by cabling the fiber. The magnitude of these effects is shown by loss curves in Fig. 5 that were calculated for distorted refractive index profiles which apply to bent lightguides with constant radii of curvature. Curves are plotted for a representative case with $\Delta = 0.3$ percent, $\Delta' = -0.2$ percent, and $a =$ 3.75 μm bent with various constant radii of curvature including $R = 3$, 5, and 10 cm. Losses (in Fig. 4 when $\lambda < 1.6$ μm) are not significant for straight lightguides with those (a, Δ, Δ') parameters. However, Fig. 5 shows that, for $\lambda > 1.6$ μm, radiation losses become greater than 0.1 dB/km for bent lightguides with $R < 10$ cm if $b/a = 6$ (solid curves); or with $R < 10$ cm if $b/a = 7$ (dashed curves).

Fig. 6 shows guidelines for a more conservative design approach that would ensure tolerably low leakage losses even when $\Delta = 0$ as for Fig. 1(c). This lightguiding structure supports a fundamental radiating leaky mode at all wavelengths because its outer cladding index is equal to the core index. Radiative leakage losses are plotted as a function of wavelength with the cladding-to-core ratio b/a as the variable parameter. These losses are never zero because the HE_{11} fundamental mode is cutoff at all wavelengths. Care must be taken to choose b/a large enough to ensure low leakage losses within the wavelength range of interest. For example, $b/a =$ 8.5 is required to keep losses below 0.1 dB/km for wavelengths shorter than 1.6 μm. Throughout this paper we have assumed that the double-clad fiber has a piecewise constant refractive

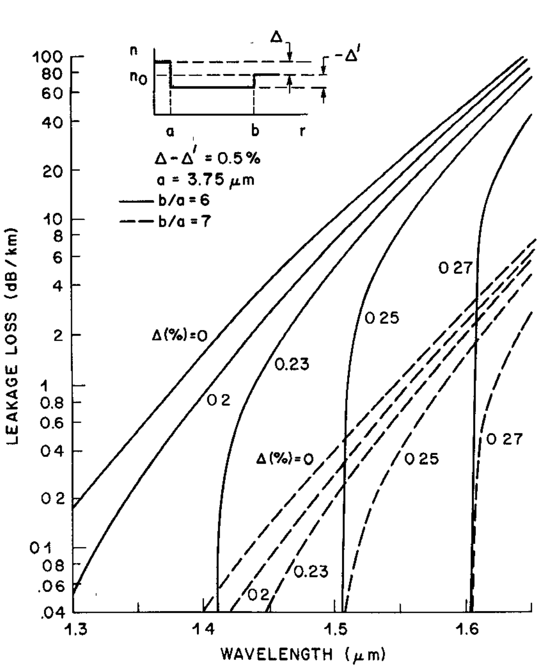

Fig. 4. Radiation leakage losses 2α(dB/km) versus wavelength $\lambda(\mu m)$ for lightguide profiles like Fig. 1(b) with $a = 3.75$ μm and $\Delta - \Delta' =$ 0.5 percent. The curves apply to different values of $\Delta = 0, 0.2, 0.23,$ 0.25, and 0.27 percent. Solid curves apply when $b/a = 6$ and dashed curves when $b/a = 7$.

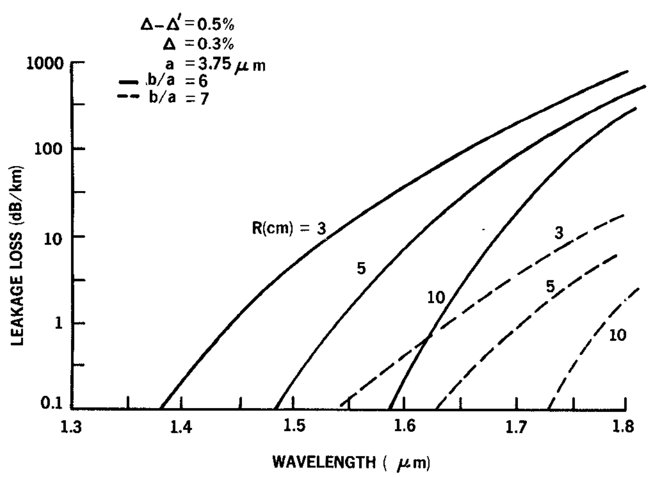

Fig. 5. Radiation leakage losses 2α(dB/km) versus wavelength $\lambda(\mu m)$ for bent lightguides with constant radii of curvature $R(cm)$, $a =$ 3.75 μm, and $\Delta - \Delta' = 0.5$ percent. Solid curves apply when $b/a = 6$ and dashed curves when $b/a = 7$.

index distribution as shown in Fig. 1. Practical fibers rarely have discontinuous refractive index distributions. Fibers with more realistic continuous refractive index profiles can be treated by solving the radial wave equation which, with the help of normalized parameters, assumes the form

$$\frac{1}{r}\frac{d}{dr}\left\{r\frac{dE}{dr}\right\} + V_3^2\,[B^2 - N^2(r)]\;E(r) = 0 \tag{14}$$

where E is the electric field, r is the normalized radius, $V_3 =$ $(b/a)\ V_1 = kb(2\Delta)^{1/2}$, B is a normalized propagation constant, and N is a normalized refractive index profile function. The significance of the normalized equation is that the actual fiber radius b, index difference Δ, and operating wavelength λ appear

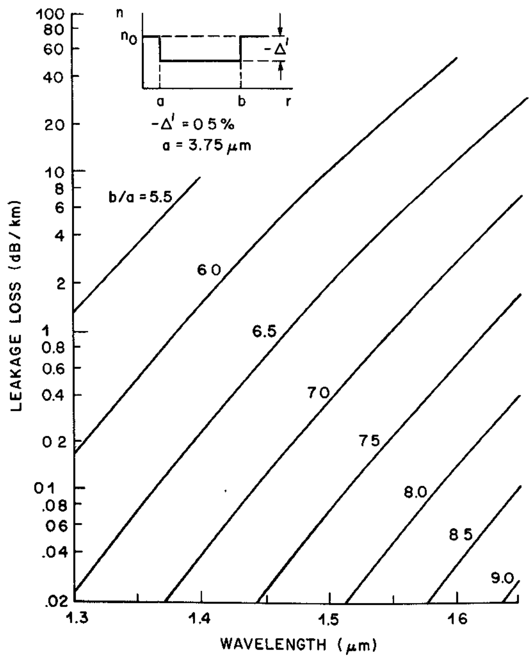

Fig. 6. Radiation leakage losses 2α(dB/km) versus wavelength $\lambda(\mu m)$ for lightguide profiles like Fig. 1(c) with $a = 3.75$ μm and $\Delta = -\Delta' =$ 0.5 percent. The curves apply to different values of b/a ($5.5 \leqslant$ $b/a \leqslant 9$).

only through the parameter V_3. Fibers with general refractive index profiles can be treated by solving (10) by using methods that have been described elsewhere [17], [18].

IV. Conclusions

The fundamental mode in a double-clad fiber can be cutoff if its inner cladding is deep enough to make its phase index smaller than the refractive index of the outer cladding. This mechanism causes light to leak out of lightguides with depressed-index claddings and can be used to explain some of the high losses that have been observed in experimental fibers.

Cutoff conditions were described in terms of normalized curves which show the HE_{11} mode cutoff V_c number plotted as a function of lightguide parameters b/a and $H = -\Delta'/\Delta$. Calculations for a specific example, $b/a = 1.43$ and $H = 2$, were used to show that cutoff wavelengths can be longer than 1.6 μm in lightguide structures with narrow and deep index wells. These are potentially useful wavelength-division-multiplexing applications which require low loss and low dispersion throughout the 1.3-1.6 μm wavelength region.

Alternatively, double-clad lightguides with wide index wells can be used to simulate conventional step-index structures. Silica fibers co-doped with germania in the core and fluorine in the cladding have attracted attention because their lightguide structure can be chosen to satisfy low dispersion requirements at any wavelength in the 1.28-1.38 μm range. However, in order to prevent high cutoff losses, the inner cladding must be made wide enough to prevent significant leakage into the outer cladding. As an example, calculations were used to show that the deposited inner cladding radius, for $a = 3.75$ μm, $\Delta = 0$, and $\Delta' = -0.5$ percent should be 8.5 times wider than the core radius in order to ensure low losses (<0.1 dB/km) for wavelengths shorter than 1.6 μm.

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Leonard G. Cohen (M'68–SM'78), for a photograph and biography, see p. 53 of the January 1982 issue of the Journal of Quantum Electronics.

Dietrich Marcuse (M'58–F'73), for a photograph and biography, see p. 43 of the January 1982 issue of the Journal of Quantum Electronics.

Wanda L. Mammel, for a photograph and biography, see p. 53 of the January 1982 issue of the Journal of Quantum Electronics.