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Attenuation of Unwanted Cladding Modes

By D. MARCUSE

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This paper contains design criteria for the suppression of cladding modes in optical fibers by means of a lossy jacket. The calculations are actually based on the slab waveguide model. However, it is believed that the results are representative, at least to order of magnitude, for the round optical fiber. It is found that the cladding modes are absorbed most effectively if the real part of the refractive index of the lossy jacket equals the refractive index of the cladding material. However, slight deviations from this optimum design are not critical.

The loss of the cladding modes depends on many parameters so that general statements as to the order of magnitude of the expected loss are hard to make. However, a loss of 1 *dB/m should be easily obtainable.*

I. INTRODUCTION

Losses in dielectric optical waveguides have been discussed by several authors.[1,2] In two earlier papers[3,4] we explored the problem of crosstalk between two parallel optical waveguides. Two types of crosstalk were considered. The directional coupler mechanism couples two dielectric waveguides even if they have no imperfections of any kind. The coupling, in this case, is caused by the exponentially decaying field tail of one guide reaching to the region of the second guide. The second mechanism causing crosstalk involves light scattering from waveguide imperfections. The light that is scattered out of the guided mode of one guide can be scattered back into the guided mode of a neighboring waveguide. Both types of crosstalk can, in principle, be reduced by placing a lossy material between the two guides. However, it was concluded that isolation of the waveguides by means of a lossy surrounding medium is really not necessary to avoid crosstalk. The waveguides must be designed in such a way that their mode losses are low. The same mechanism that influences crosstalk also influences the mode loss. For example, if two guides couple appreciably by means of the directional coupler mechanism their mode fields penetrate each other to a considerable extent. Adding loss to the surrounding medium thus also causes added loss to the mode field. In fact, if the loss in the surrounding medium is needed to reduce crosstalk it simultaneously adds so much loss to the guided mode as to defeat its purpose. The cladding of the fiber must thus be made sufficiently thick to protect the guided mode from losses of its environment. But a sufficiently thick cladding also provides adequate protection against crosstalk. The scattering crosstalk problem, on the other hand, does not benefit from a lossy surrounding medium for different reasons. Even if the cladding is made sufficiently thick to protect the guided mode from losses of the surrounding medium it is still possible to obtain substantial scattering crosstalk. However, the same mechanism that produces scattering crosstalk also causes scattering loss to the guided modes. Except for the unlikely case of a systematic periodic distortion that persists throughout the entire length of both waveguides, the scattering mode loss is more critical than the scattering crosstalk so that it is necessary to build a guide with sufficient accuracy to hold scattering losses down. Once this is achieved scattering crosstalk is no longer a problem.

It thus appears as though it were not necessary to surround the members of a bundle of waveguides with a lossy medium in order to prevent crosstalk provided that the waveguides are built with low scattering losses and with a sufficiently thick cladding. However, there is one more reason why losses in the surrounding medium may be desirable. We have so far ignored the possibility that power which is scattered out of the core of the waveguide is trapped in the cladding. These cladding modes are undesirable for two reasons. They couple some of their power back into the core causing problems of delay distortion of the guided core modes. In addition, these modes may reach the end of the waveguide and there enter the detector giving further rise to unwanted, delayed signals. It is thus important to suppress cladding modes by providing each waveguide with a lossy jacket.

We must keep in mind that the loss requirements for the cladding modes are more stringent than the loss requirements for the core modes. A loss factor that is prohibitively high for a core mode may be far too low for a cladding mode. The cladding mode can be harmful even if it is too lossy to propagate through the entire length of the waveguide by itself. Cladding modes are continuously excited and reconvert to core modes throughout the entire length of the waveguide so that their presence is undesirable not only at the end of the waveguide but throughout the entire length of the guide. It is thus desirable to ensure cladding mode losses far higher than the losses that appear excessive if they should occur for core modes.

A very effective way of suppressing cladding modes would be to provide the waveguides of the cable with a surrounding medium whose index is higher than that of the cladding. In this case the light can no longer be trapped in the cladding but would rapidly escape into the surrounding medium. However, if it were not attenuated there it would still be harmful since some of it can scatter back into guided modes and some of it may reach the detectors at the end of the guide giving rise to crosstalk and delay distortion.

The next best thing, therefore, is designing a surrounding medium or jacket with a refractive index whose real part nearly equals the index of the cladding but which is sufficiently lossy to attenuate power that tries to travel in it. This paper tries to provide the design criteria necessary to build effective lossy jackets for the suppression of cladding modes.

II. CLADDING MODE LOSS FORMULA

Our interest is, of course, directed toward the cladding modes of round optical fibers. In fact, the formula for core mode losses in round optical fibers provided in Ref. 3 can be used to calculate cladding mode losses in fibers with infinitely thick jacket by letting the refractive indices of cladding and surrounding medium coincide and by shrinking the cladding thickness to zero. However, a discussion of the cladding mode losses for round optical fibers with finite jacket thickness is complicated due to the complexity of the round fiber equation. As always, the slab waveguide is much easier to treat than the round optical fiber. Results obtained for the slab waveguide model are applicable to the round fiber at least as order of magnitude estimates. Since order of magnitude estimates are all that we need in the present situation and since the formulas for the slab waveguide are so much easier to evaluate we shall base our discussion of cladding mode losses on the slab waveguide model.

The slab waveguide model to be studied is schematically shown in Fig. 1. We ignore the core of the waveguide since it does not contribute appreciably to the propagation behavior of the cladding modes. The refractive index of the fiber core is so close to the refractive index of the cladding in most fibers of interest for communications purposes that we can ignore the core altogether. The cladding mode losses are caused by the fact that the reflection of the electromagnetic energy at the boundary

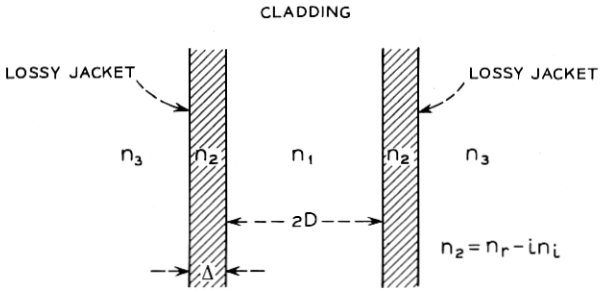

Fig. 1—Sketch of a dielectric waveguide (core not shown) with a lossy jacket.

between cladding and jacket is not 100 percent efficient. It is thus the plane wave reflection coefficient at the cladding jacket interface that determines the cladding mode losses. The reflection coefficient is higher for waves whose electric field vector is polarized parallel to the dielectric interface (TE modes) compared to waves whose magnetic vector is parallel to the interface (TM modes). The modes with the higher reflection coefficient have lower loss. The TE modes have lower loss than the TM modes. It is thus sufficient to study TE modes since the TM mode losses must be higher. A design that succeeds in suppressing TE modes does suppress TM modes even more effectively.

In order to obtain the mode losses for the structure shown in Fig. 1 we study the reflection coefficient of a plane wave incident on the structure shown in Fig. 2. The electric field vector is given by the equations:

$$E_y = Ae^{-i(\beta z + \kappa x)} + Be^{-i(\beta z - \kappa x)} \qquad x < 0, \tag{1}$$

$$E_y = Ce^{-i(\beta z + \sigma x)} + Fe^{-i(\beta z - \sigma x)} \qquad 0 \leqq x \leqq \Delta, \tag{2}$$

$$E_y = Ge^{-i(\beta z + \rho x)} \qquad \Delta \leqq x \leqq \infty. \tag{3}$$

The time dependent factor exp $(i\omega t)$ has been suppressed. The parameters κ, σ, and ρ are defined by the equations:

$$\kappa = (n_1^2 k^2 - \beta^2)^{\frac{1}{2}}, \tag{4}$$

$$\sigma = (n_2^2 k^2 - \beta^2)^{\frac{1}{2}}, \tag{5}$$

$$\rho = (n_3^2 k^2 - \beta^2)^{\frac{1}{2}}, \tag{6}$$

with

$$k = \omega(\epsilon_0 \mu_0)^{\frac{1}{2}} = 2\pi/\lambda_0 . \tag{7}$$

The magnetic field components are obtained from E_y with the help of

$$H_x = -\frac{i}{\omega\mu_0}\frac{\partial E_y}{\partial z}, \qquad H_z = \frac{i}{\omega\mu_0}\frac{\partial E_y}{\partial x}. \tag{8}$$

The boundary conditions at the two dielectric interfaces determine the relations between the amplitude coefficients:

$$B = \frac{\sigma(\kappa - \rho)\cos\sigma\Delta + i(\kappa\rho - \sigma^2)\sin\sigma\Delta}{\sigma(\kappa + \rho)\cos\sigma\Delta + i(\kappa\rho + \sigma^2)\sin\sigma\Delta} A, \tag{9}$$

$$C = \frac{\kappa(\sigma + \rho)e^{i\sigma\Delta}}{\sigma(\kappa + \rho)\cos\sigma\Delta + i(\kappa\rho + \sigma^2)\sin\sigma\Delta} A, \tag{10}$$

$$F = \frac{\kappa(\sigma - 1)e^{-i\sigma\Delta}}{\sigma(\kappa + \rho)\cos\sigma\Delta + i(\kappa\rho + \sigma^2)\sin\sigma\Delta} A, \tag{11}$$

$$G = \frac{2\kappa\sigma e^{i\rho\Delta}}{\sigma(\kappa + \rho)\cos\sigma\Delta + i(\kappa\rho + \Delta^2)\sin\sigma\Delta} A. \tag{12}$$

The field that is described by the equations (1) through (12) is the cladding mode field of the waveguide. The type of mode that actually results depends on the width $2D$ of the guide and on the angle at which the plane wave travels in the slab; that is, it depends on the ratio κ/β. For the calculation of the mode losses we do not need to know this ratio very accurately. It is clear, however, that lossless modes satisfy the

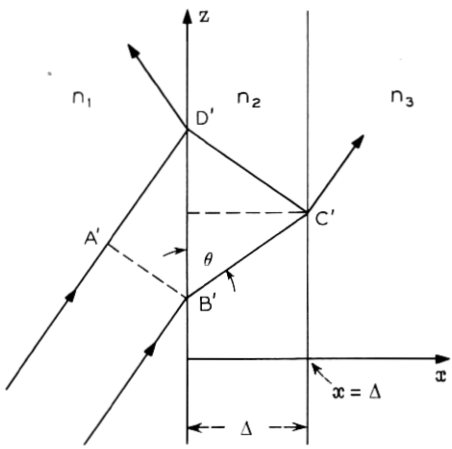

Fig. 2—This diagram shows the interference between an incident wave and the wave that has penetrated into the jacket.

requirement $|A| = |B|$. The transverse field distribution in the slab at $-D \leqq x \leqq D$ is thus a standing wave. Since it is very hard to achieve a large loss coefficient α for the cladding modes we can assume $\alpha \ll 1/\lambda$ and have

$$\frac{|A| - |B|}{|A|} \ll 1. \tag{13}$$

In order to obtain the mode loss, we calculate the power flow along the waveguide axis,

$$P_z = \mathrm{Re}\left\{-\frac{1}{2}\int_{-2D}^{0} E_y H_x^* \, dx\right\} = \mathrm{Re}\left\{\frac{\beta}{2\omega\mu}\int_{-2D}^{0} |E_y|^2 \, dx\right\}. \tag{14}$$

Re indicates the real part of the quantity in brackets. The integral is extended only over the cladding region of the waveguide assuming that most of the power is contained in this region. For reasonably low loss this condition is satisfied. Using (1) and (13) we obtain

$$P_z \approx \frac{2\beta D}{\omega\mu} |A|^2. \tag{15}$$

The amount of power at the cladding boundary that flows per unit area out of the waveguide is given by

$$S_x = \mathrm{Re}\,\{\tfrac{1}{2}E_y H_z^*\}_{x=0} = \frac{\kappa |A|^2}{2\omega\mu}\left(1 - \left|\frac{B}{A}\right|^2\right). \tag{16}$$

The power loss coefficient 2α (α is the amplitude loss coefficient) is

$$2\alpha = \frac{2S_x}{P_z}. \tag{17}$$

The factor 2 on the right-hand side of (17) takes account of the fact that equal amounts of power are lost at the cladding jacket interface on either side of the waveguide. Substitution of (15) and (16) into (17) results in the desired formula for the loss of the cladding modes:

$$2\alpha = \frac{\kappa}{2\beta D}\left(1 - \left|\frac{B}{A}\right|^2\right). \tag{18}$$

The coefficient B/A is obtained from (9). We consider only the case that the medium outside of the waveguide jacket has the lowest refractive index, $n_3 < |n_2|$ and $n_3 < n_1$. We thus have

$$\rho = -i\gamma \tag{19}$$

with

$$\gamma = (\beta^2 - n_3^2 k^2)^{\frac{1}{2}} \tag{20}$$

being a real quantity. We set

$$\sigma = u - iv \tag{21}$$

with u and v both real and positive. In the limit of an infinitely thick jacket, $\Delta \to \infty$, we obtain from (9) and (18)

$$2\alpha = \frac{2\kappa^2 u}{\beta D(u^2 + v^2 + \kappa^2 + 2u\kappa)}. \tag{22}$$

It is interesting to consider two different alternatives. First we assume that

$$\mathrm{Re}(n_2^2 k^2) > \beta^2. \tag{23}$$

The refractive index of the jacket material is a complex number

$$n_2 = n_r - i\,\frac{\alpha_i}{k}. \tag{24}$$

α_i is the amplitude loss coefficient of a plane wave traveling in the jacket. We assume

$$n_r \gg \frac{\alpha_i}{k} \tag{25}$$

and obtain from (5) and (21)

$$u = [\tfrac{1}{2}\sigma_0^2 + \tfrac{1}{2}(\sigma_0^4 + 4n_r^2 k^2 \alpha_i^2)^{\frac{1}{2}}]^{\frac{1}{2}} \tag{26}$$

and

$$v = [-\tfrac{1}{2}\sigma_0^2 + \tfrac{1}{2}(\sigma_0^4 + 4n_r^2 k^2 \alpha_i^2)^{\frac{1}{2}}]^{\frac{1}{2}} \tag{27}$$

with

$$\sigma_0 = (n_r^2 k^2 - \beta^2)^{\frac{1}{2}}. \tag{28}$$

It is apparent from (22) that α vanishes for $u = 0$ and for $u = \infty$. This indicates that 2α must assume a maximum as a function of u. By differentiation of (22) we find that the maximum is located at

$$u_{\max} = (\kappa^2 + v^2)^{\frac{1}{2}}. \tag{29}$$

The maximum value $2\alpha_{\max}$ that corresponds to (29) is given by

$$2\alpha_{\max} = \frac{\kappa^2}{\beta D[(\kappa^2 + v^2)^{\frac{1}{2}} + \kappa]}. \tag{30}$$

In order to express the condition for $u_{\max}$ in terms of the refractive indices of the waveguide we square (29) and substitute (26) on the left-hand side and (27) on the right-hand side of the squared equation. We obtain the solution

$$\sigma_0 = \kappa. \tag{31}$$

Comparison of (4) and (28) shows that the maximum cladding mode loss for an infinitely thick jacket is obtained if

$$n_r = n_1 , \tag{32}$$

that is, for the case that the real part of the refractive index of the jacket is equal to the refractive index of the cladding. The requirement of an infinite jacket thickness means only that the effect of the boundary between the jacket and the outside medium must be negligible. As a practical matter this condition is satisfied if the product $\alpha_i \Delta$ is larger than about 10 dB. For an infinitely wide jacket and as long as the condition (23) holds we obtain maximum loss for vanishing v, that is, in the case of a lossless jacket. Increasing the loss of the jacket decreases the loss of the cladding modes slightly as long as v remains smaller than κ. For very high losses of the jacket material the cladding mode loss decreases with increasing jacket loss. This consideration shows that the loss of the jacket material must not be made too high.

In the opposite case

$$\mathrm{Re}(n_2^2 k^2) < \beta^2 \tag{33}$$

we obtain

$$u = [-\tfrac{1}{2}\,\delta^2 + \tfrac{1}{2}(\delta^4 + 4n_r^2 k^2 \alpha_i^2)^{\frac{1}{2}}]^{\frac{1}{2}} \tag{34}$$

and

$$v = [\tfrac{1}{2}\,\delta^2 + \tfrac{1}{2}(\delta^4 + 4n_r^2 k^2 \alpha_i^2)^{\frac{1}{2}}]^{\frac{1}{2}} \tag{35}$$

with

$$\delta = (\beta^2 - n_r^2 k^2)^{\frac{1}{2}}. \tag{36}$$

For vanishing loss in the jacket we now obtain $u = 0$ so that the cladding modes propagate without loss in this case. The waves are totally internally reflected at the interface between cladding and jacket. The condition for $u_{\max}$ given by (29) can now not be satisfied. For numerical calculation we shall always assume that the cladding modes are so tightly guided that we can use

$$\beta = n_1 k. \tag{37}$$

Far from cutoff the values for κ are obtained from[5]

$$\kappa D = (\nu + 1)\frac{\pi}{2} \tag{38}$$

with integer values of ν. Even integers of ν belong to even modes while odd integers belong to odd modes. Equations (22) and (30) show that the lowest order mode ($\nu = 0$) propagates with the lowest loss. Since we are interested in maximizing the losses of all the modes it is thus sufficient to consider the loss of the lowest order even TE mode and use

$$\kappa D = \frac{\pi}{2}. \tag{39}$$

For finite thickness of the jacket material and sufficiently low loss the cladding mode losses vary as a function of cladding thickness Δ. Figures 3 and 4 show these loss fluctuations for the case $kD = 50$, $n_1 = 1.6$, $n_r = 1.65$, and $n_3 = 1$. The jacket loss was assumed to be $2\alpha_j D = 0.1$ dB in case of Fig. 3 and 1 dB in case of Fig. 4. These loss variations as a function of jacket thickness complicate the design of an optimum jacket. Since we need a certain minimum loss for the effective suppression of all cladding modes we are interested in the minimum values of the loss. It is thus necessary to find the position of the loss minima of equation (18). Since it is difficult to find the minimum values mathematically from the loss expression we use a physical argument based on ray optics for the case $n_r > n_1$.

Figure 2 shows the geometry of the problem. Minimum loss is obtained if the light rays that are reflected from the cladding-jacket boundary add in phase to the light rays that penetrate into the jacket, are reflected at its outer boundary, and reenter the cladding. The condition for minimum cladding mode loss can thus be stated as follows

$$(n_r k\eta + \phi_2) - (n_1 k\xi + \phi_1) = 2\nu\pi. \tag{40}$$

The distance from point A' to point D' in Fig. 2 is ξ, the distance from point B' to C' and on to D' is η, and the phase angles ϕ_1 and ϕ_2 are the additional phase shifts that the wave suffers on reflection from the interface between cladding and jacket and between jacket and the outside medium. The number ν must be an integer. Using simple geometry we obtain

$$\eta = \frac{2\Delta}{\sin\theta}. \tag{41}$$

The angle of the incident ray is shown vastly exaggerated in Fig. 2.

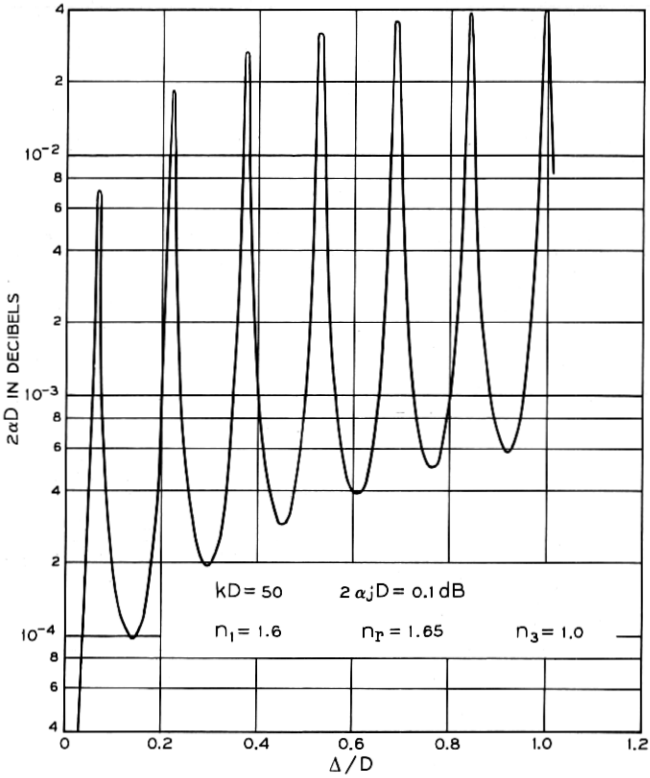

Fig. 3—Fluctuation of cladding mode loss as a function of jacket thickness Δ. (D = cladding thickness; $2\alpha_j$ = power loss coefficient of the jacket material; k = propagation constant of free space; n_1, n_r, and n_3 are respectively the refractive indices of the cladding, the (real part) of the jacket, and the outside medium). $kD = 50$, $2\alpha_j D = 0.1$ dB, $n_1 = 1.6$, $n_r = 1.65$, $n_3 = 1.0$.

For low-order cladding modes the angle between the incident ray and the interface is very nearly zero. We thus obtain from Snell's law

$$\sin \theta = \left[1 - \frac{n_1^2}{n_r^2}\right]^{\frac{1}{2}}. \tag{42}$$

Because the input ray intercepts the interface at grazing angles we can approximate ξ as follows

$$\xi = 2\Delta \cot \theta = 2\Delta \frac{n_1}{[n_r^2 - n_1^2]^{\frac{1}{2}}}. \tag{43}$$

The additional phase angle on reflection from the optically denser jacket is

$$\phi_1 = \pi. \tag{44}$$

The phase angle ϕ_2 is more complicated. From the Fresnel formulas for the transmission of a plane wave across a dielectric interface we obtain

$$\phi_2 = -2 \arctan \left[\frac{(n_1^2 - n_3^2)^{\frac{1}{2}}}{(n_r^2 - n_1^2)^{\frac{1}{2}}} \right]. \tag{45}$$

Collecting all these equations we obtain from (40) the jacket width that minimizes the cladding mode loss:

$$\Delta_{\min} = \frac{\nu\pi + \dfrac{\pi}{2} + \arctan \left\{ \dfrac{(n_1^2 - n_3^2)^{\frac{1}{2}}}{(n_r^2 - n_1^2)^{\frac{1}{2}}} \right\}}{k(n_r^2 - n_1^2)^{\frac{1}{2}}}. \tag{46}$$

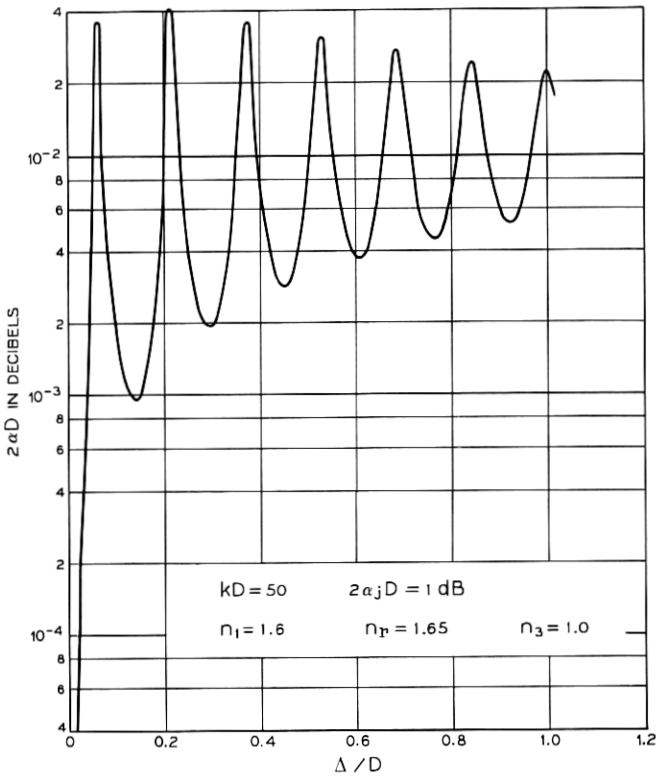

Fig. 4—Same as Fig. 3 except that $2\alpha_j D = 1$ dB.

Numerical values of (46) agree with the position of the minima appearing in Figs. 3 and 4.

III. NUMERICAL RESULTS

The theory presented on the preceding pages contains the information for the design of lossy jackets for the purpose of suppressing cladding modes. Because of the large number of independent parameters entering equations (9) and (18) it is impossible to draw curves covering all possible cases of interest. We are thus limiting the discussion of numerical results to a few cases hoping to show the trend and the order of magnitude of the cladding mode losses that may be obtainable.

All curves are calculated for a cladding index $n_1 = 1.6$ and an index of $n_3 = 1$ for the surrounding medium. Most curves apply to the case $kD = 50$. Those curves are drawn as solid lines. Broken curves are examples for $kD = 100$ and dash-dotted curves apply to $kD = 500$. A comparison between these three kD values gives some indication of the dependence of the cladding mode losses on the kD parameter.

The cladding mode loss $2\alpha D$ for a guide length equal to the half width D of the cladding is shown in Fig. 5 for $n_r/n_1 > 1$ as a function of the jacket loss $2\alpha_i\Delta$. (D = cladding half width, Δ = jacket thickness, both losses are expressed in dB). Figure 5 was computed from (9), (18), and (46) for the minima of the fluctuating loss curves (compare Figs. 3 and 4). It is important to remember that the first loss minimum occurs for $\Delta_{\min}$ of (46) for $\nu = 0$. The curves of Fig. 5 do not apply to values of the jacket thickness Δ that are much smaller than this minimum thickness. The loss curves shown in Figs. 3 and 4 drop off very rapidly for Δ values that are smaller than the value at the first minimum so that the mode losses obtained from Fig. 5 would be much higher than the actual losses if the figure were applied to Δ values that are smaller than the first minimum. For jackets that are thicker than the minimum value (46) with $\nu = 0$ the curves of Fig. 5 show the lowest possible cladding mode loss. The loss curves shown in Fig. 5 are correct for small values of $2\alpha_i D$ (note that we have just replaced Δ with D). As long as it stays below a certain critical value the curves are independent of $2\alpha_i D$. For larger values the cladding mode losses decrease with increasing $2\alpha_i D$. The critical value is different for each curve shown in Fig. 5. The dependence of the cladding mode losses on $2\alpha_i D$ is shown in Fig. 6. This figure presents the values of the cladding mode losses for infinite jacket thickness Δ as a function of $2\alpha_i D$. It is apparent from Fig. 5 that the cladding mode losses become independent of the jacket thickness for

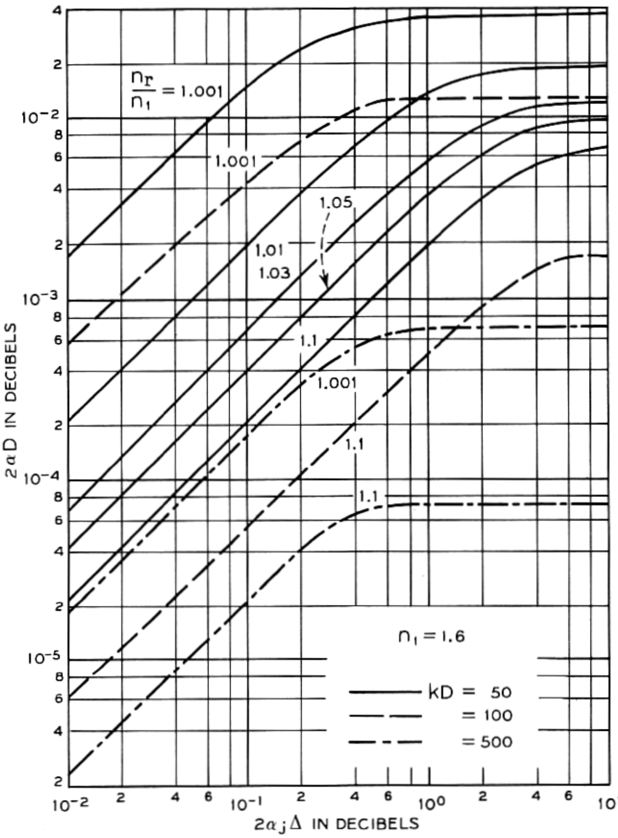

Fig. 5—The minimum cladding mode loss as a function of the jacket loss $2\alpha_j\Delta$ for different values of $n_r/n_1 > 1$.

sufficiently large values of Δ. Figure 6 shows the mode losses of Fig. 5 after they have leveled off ($\Delta \rightarrow \infty$). It can be seen that the cladding mode losses become less sensitive to the value of $2\alpha_i D$ for increasing values of the jacket-to-cladding index ratio n_r/n_1. However, the loss curves for $n_r/n_1 = 1.001$ become dependent on the jacket loss coefficient α_j already for $2\alpha_i D = 1$ dB. It is important to keep this in mind when using Fig. 5.

Comparison of the dash-dotted, broken, and solid lines in Figs. 5 and 6 shows that the cladding mode loss depends on the kD parameter as $(kD)^{-2}$ for $\Delta \rightarrow \infty$. It is very hard to see this relation from (18); however

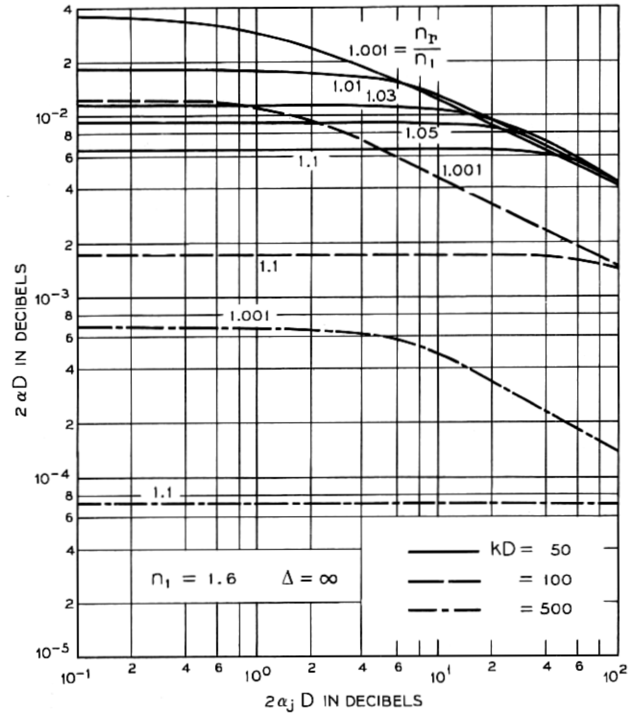

Fig. 6—Cladding mode losses for infinitely thick jacket, $\Delta \to \infty$, as functions of the jacket loss parameter $2\alpha_j D$ for $n_r/n_1 > 1$.

it can be seen from (22) and (26) for small values of v. It is interesting to observe that the maximum loss (30) depends on kD only as $(kD)^{-1}$.

In order to obtain a feeling for the absolute loss values that can be achieved let us assume that the cladding half thickness is $D = 10\mu m$. The loss factor $2\alpha D = 10^{-5}$ dB thus corresponds to a cladding mode loss of $2\alpha = 1$ dB/m. Cladding mode losses well in excess of 1 dB/m are thus easily obtainable. In fact it appears possible to design jackets that provide cladding mode losses of 100 to 1000 dB/m.

So far we have considered jackets with a refractive index whose real part is larger than the index of the cladding material. If the real part of the jacket index is smaller than the cladding index, $n_r/n_1 < 1$, the cladding mode losses are no longer even approximately independent of $2\alpha_j D$. The loss curves can thus not be drawn as functions of $2\alpha_j \Delta$. Figures 7, 8, and 9 are representations of the cladding mode losses for $n_r/n_1 < 1$ as functions of Δ/D. The parameter $2\alpha_j D$ is used to label the different curves in each figure. Comparison shows that for equal values of kD and $2\alpha_j D$ the loss curves are nearly identical for all three figures for low values of Δ/D. The leveling off of the curves for large values of Δ/D is, however, quite different for each value of n_r/n_1. The dependence of the cladding mode loss for $n_r/n_1 < 1$ as a function of $2\alpha_j D$ for $\Delta \to \infty$ is shown in Fig. 10. The loss curves of Fig. 10 show maxima that shift as a function of n_r/n_1. The mode loss $2\alpha D$ is not an oscillating function of the jacket thickness if $n_r/n_1 < 1$. The curves shown in Figs. 7 through 9 are thus not the loss minima but the actual loss values as functions of Δ/D.

The dependence on the kD parameter for $n_r/n_1 < 1$ can be seen from

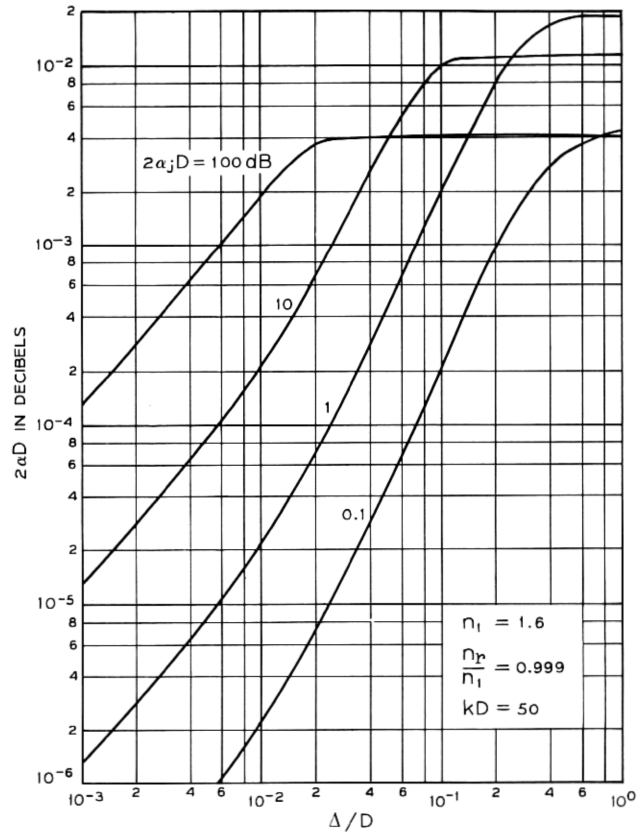

Fig. 7—Cladding mode losses as functions of the jacket thickness for $n_r/n_1 = 0.999$.

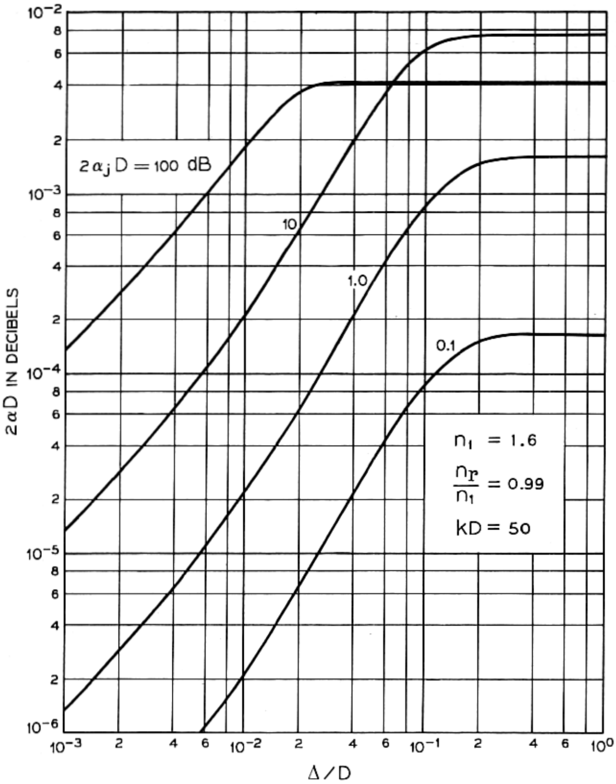

Fig. 8—Cladding mode losses as functions of the jacket thickness for $n_r/n_1 = 0.99$.

the figures to be as $(kD)^{-3}$ for $\Delta \rightarrow \infty$ while the dependence for small values of Δ/D is as $(kD)^{-2}$.

Even for jackets with a refractive index whose real part is smaller than the cladding index, losses well in excess of 1 dB/m are obtainable. However a comparison of the two cases, $n_r/n_1 > 1$ and $n_r/n_1 < 1$, shows that jackets with a refractive index higher than the cladding index provide more losses to the cladding modes.

Lossy jackets need not be very thick to be effective. For example, for $kD = 50$ and $\Delta/D = 0.1$ (for $D = 10\mu$m this would correspond to a jacket 1μm thick), we could choose $n_r/n_1 = 1.1$ and obtain a cladding mode loss of $2\alpha D = 2 \times 10^{-3}$ dB (or 200 dB/m) with a total jacket loss of $2\alpha_j\Delta = 1$ dB or $2\alpha_j D = 10$ dB. Figure 6 shows that the curve with $n_r/n_1 = 1.1$ is still constant at $2\alpha_j D = 10$ dB so that Fig. 5 is applicable for a jacket loss of that magnitude. Increasing the jacket thickness to much larger values would triple the cladding mode losses (in dB) in this case. An increase of kD to $kD = 500$ reduces the loss to 7.2×10^{-5} dB (or 7.2 dB/m).

IV. CONCLUSIONS

Losses for cladding modes have been calculated with the help of a slab waveguide model with a lossy jacket. It has been found that the cladding mode losses are maximized if the real part of the refractive index of the jacket material equals the refractive index of the cladding material. However, high cladding mode losses can be achieved with jackets whose real part of the refractive index is either lower or higher than that of the cladding material. Losses in excess of 1 dB/m are easily

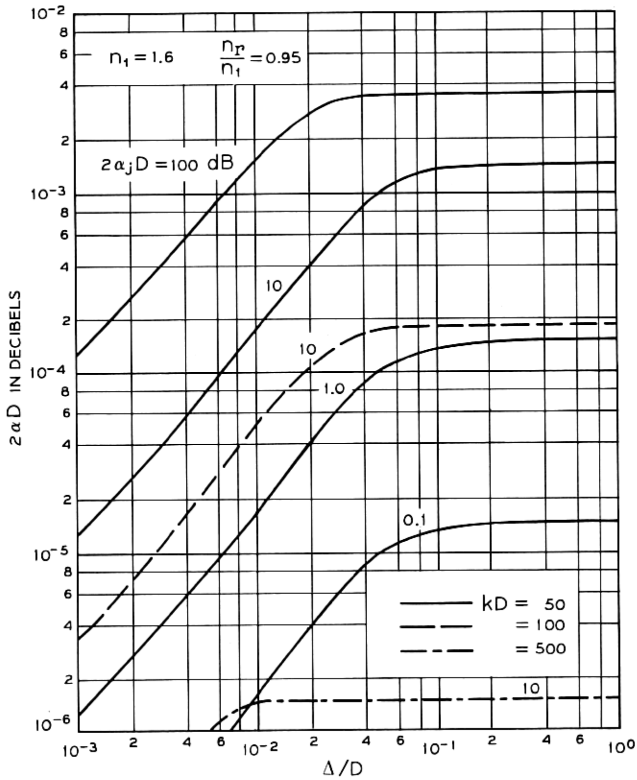

Fig. 9—Cladding mode losses as functions of the jacket thickness for $n_r/n_1 = 0.95$.

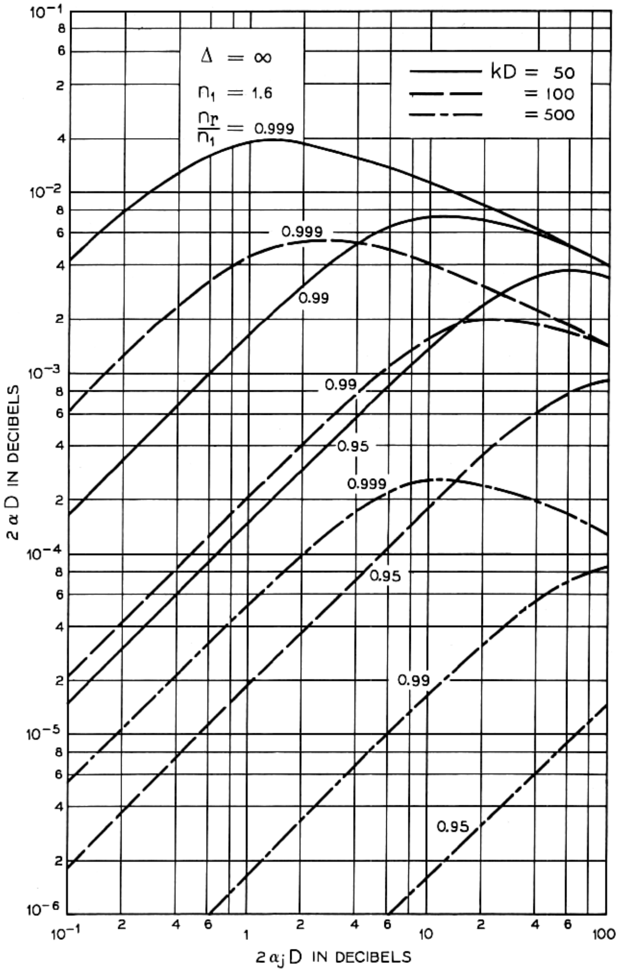

Fig. 10—Cladding mode losses for infinitely thick jacket as functions of the jacket loss parameter $2\alpha_j D$ for $n_r/n_1 < 1$.

achieved. A careful design should make it possible to obtain cladding mode losses between 100 and even up to 1000 dB/m, depending on the kD value at which the fiber is operated.

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