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Effect of loss on propagation in multimode fibres

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SUMMARY

An analysis is given of propagation in multimode optical fibres having finite transmission loss. Using experimentally-deduced values for the cladding loss, fibre dispersions are calculated for a range of input beam widths and are compared with experiment. It is shown that the core loss has little effect on dispersion. Cladding loss reduces dispersion for a relatively small increase in attenuation, while dispersion and attenuation become non-linear functions of length.

1 Introduction

Apart from attenuation the most important parameter to consider in the application of optical fibres to long-distance communications is that of bandwidth. For single-mode cladded fibres the bandwidth depends on mode and material dispersions as well as on the frequency spread of the source and estimates have been made for various configurations[1,2] resulting in predicted values of tens of gigahertz per kilometre for a monochromatic source, falling to less than 1 GHz/km for semiconductor lasers of practical linewidths. In graded-index fibres very large bandwidths are possible[3] when a monochromatic Gaussian input beam is correctly matched to the characteristic mode of the fibre and is launched accurately along the axis. However, for less than perfect launching conditions, or in the presence of mode conversion, effectively multimode propagation occurs so that the dispersion is determined by the group delay between modes and the predicted bandwidth[3] falls to a few gigahertz per kilometre and this has been confirmed by experiment.[4,5]

The bandwidth to be expected of cladded multimode fibres was originally expected to be quite small, < 10 MHz/km, but recent measurements have shown[6] that with a monochromatic Gaussian beam, and with careful optimization of the launching conditions, values approaching 1 GHz/km are possible, although there seems to be a limiting effect due to mode conversion caused by bending of the fibre. In addition the fibres on which the measurements were made, even though exhibiting the low attenuation of 5·8 dB/km, have a high-loss cladding thereby producing a mode-filtering action which enhances[7,8] the bandwidth. In order to estimate the effect of such mode filtering on pulse dispersion and overall attenuation, and to examine whether the technique can be usefully applied in practice, we present here an analysis for propagation in a cladded, multimode optical fibre having a finite cladding and core loss.

2 Generalized Analysis

A modal analysis is complicated by the large number of possible modes in the fibres under consideration which may have core diameters between 30 μm and 100 μm compared with input wavelengths of less than 1 μm. A simplified approach is therefore taken in which the input beam is represented by a bundle of rays which are assumed to propagate along the fibre by geometrical reflexion at the core/cladding interface, provided that they fall within the numerical aperture of the fibre. The details of the theory have already been reported[9] and will not be repeated here. It has been used to obtain the impulse response for sources having Gaussian and Lambertian spatial distributions and for a source having a Gaussian temporal, as well as spatial, distribution. Numerical results have also been shown graphically for typical lossless fibre parameters and good agreement is obtained with experiment for cases where the effect of fibre loss is not serious. The theory is now applied to fibres having finite core and cladding loss and numerical results are derived for a particular combination. After deducing a value for the cladding loss from a

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probing beam experiment, a comparison is made between theory and measurement for dispersion when the input pulses are derived from a TEM_{00} mode-locked helium/neon laser.

3 Application of Theory to Lossy Fibres

As indicated above, a ray propagation model is adopted in which a ray at an angle θ to the axis, in a core of refractive index n_1, propagates by successive reflexions at the interface between the core and the cladding (refractive index n_2) providing that it falls within the numerical aperture of the fibre. The analysis assumes that propagation is by meridional rays, i.e. that there are no skew rays, which is reasonable for a Gaussian beam launched axially. Secondly, it implies that the fibre axis is straight and there is no mode conversion. In most multimode fibres the latter process could well be the dominant factor determining the bandwidth but it is ignored here since the purpose of the analysis is to isolate the effect of mode filtering and to examine its influence on dispersion and attenuation. The results are applicable to the fibres made in these laboratories, since the degree of mode conversion due to geometrical imperfections has been shown to be small, but may not necessarily apply to other fibres.

For a spatially Gaussian input beam of wavelength λ and spot size ω_0 at the beam waist, the corresponding far-field semi-angular beam width is $\theta_0 = \lambda/\pi\omega_0$. If the input pulse amplitude varies with time as

$$G_\mathrm{i}(t) = G_1 \exp(-2t^2/a^2) \qquad (1)$$

and the total input pulse energy is E_0 so that

$$E_0 = \int_{-\infty}^{\infty} G_\mathrm{i}(t)\,\mathrm{d}t \qquad (2)$$

then for a fibre of length L the output pulse amplitude varies[9] with time as

$$G_0(t) = 2\alpha E_0 \exp[\alpha(1-2t^2/a^2\beta^2\gamma)] \times \int_1^{n_1/n_2} x \exp[-\gamma(\beta x - 2t^2/a^2\gamma)]T[\theta(n_1 Lx/c)]\,\mathrm{d}x \qquad (3)$$

where $\alpha = 2/\tan^2\theta_0$

$\beta = n_1 L/c$

$\gamma = \alpha/\beta^2 + 2/a^2$

and $T(\theta)$ is the transmission factor of the rays along the fibre as a function of θ It should again be noted that for axial launching of Gaussian beams there are no skew rays so that the transmission and reflexion factors are a function only of θ. For a skew ray they are functions of the angle which the ray makes with the interface as is emphasized in Section 4. The main causes of ray attenuation are absorption in the core, scattering in the core and at the core/cladding interface, together with imperfect reflexion at the interface due to finite cladding loss. The effects of absorption and scattering in the core can be represented by an effective core loss coefficient α_c and of imperfect reflexion and scattering at the interface by a reflexion factor $R(\theta)$. The ray transmission factor can thus be written

$$T(\theta) = [R(\theta)]^{\frac{L\tan\theta}{d}} . \exp(-\alpha_\mathrm{c} L \sec\theta) \qquad (4)$$

where d is the core diameter, $(L/d)\tan\theta$ is the number of reflexions at the interface and $L\sec\theta$ is the path in the core.

For a given shape of input pulse the output pulse distribution, and hence the dispersion, may be found by substituting eqn. (4) into eqn. (3) and evaluating the resulting expression.

The reflexion factor $R(\theta)$, however, depends on the state of polarisation of the reflecting ray. Thus if the complex refractive index of the cladding is denoted by $(n_2 - ik)$ then for rays with polarization perpendicular to the plane of incidence on the core/cladding interface the reflexion factor is

$$R_\perp(\theta) = \left|\frac{n_1 \sin\theta - i[n_1^2\cos^2\theta - (n_2-ik)^2]^{\frac{1}{2}}}{n_1 \sin\theta + i[n_1^2\cos^2\theta - (n_2-ik)^2]^{\frac{1}{2}}}\right|^2 \qquad (5a)$$

and for polarization parallel to the plane of incidence

$$R_\parallel(\theta) = \left|\frac{(n_2-ik)^2 \sin\theta - in_1[n_1^2\cos^2\theta - (n_2-ik)^2]^{\frac{1}{2}}}{(n_2-ik)^2 \sin\theta + in_1[n_1^2\cos^2\theta - (n_2-ik)^2]^{\frac{1}{2}}}\right|^2 \qquad (5b)$$

where k is the loss coefficient in the cladding and is related to the bulk cladding absorption coefficient α_k by $\alpha_k = 4\pi k/\lambda_0$. In the analysis which follows the light is assumed to be randomly polarized so that $2R(\theta) = R_\perp(\theta) + R_\parallel(\theta)$.

4 Dispersion in Liquid-core Fibre

The theory is now applied to the case of a fibre[10] consisting of hexachlorobuta-1,3-diene in Chance-Pilkington ME1 cladding and made in these laboratories. The minimum attenuation is[11] 5·8 dB/km, which gives an upper limit to the minimum core attenuation, and while it is known that the cladding loss is several orders of magnitude larger than this the actual value is not known accurately.

Measurements of dispersion have been made with a mode-locked helium/neon laser operating in the TEM_{00} mode at 0·633 μm and producing pulses of 0·65 ns half-width. The core diameter was 50 μm, $n_1 = 1{\cdot}551$ and $n_2 = 1{\cdot}4846$. The dispersion calculations therefore assume these values.

At this wavelength the total fibre attenuation is 35 dB/km and even if this were all due to the core the resulting effect on dispersion would be negligible. Thus for a core loss of this magnitude the greater path length of a ray at an angle to the axis of, say, 5° compared with that of the axial ray, produces a differential attenuation of only 0·1 dB/km. It may be concluded therefore, and more detailed calculations have also shown, that the core attenuation has little effect on the dispersion and only reflexion loss at the interface need be considered.

Since the exact value for the loss of the internal surface layer of the fibre cladding was not known, values for the reflexion loss were obtained directly by measuring the variation in attenuation of a narrow beam as the input angle of incidence θ was changed. A white light source, followed by a 0·64 μm filter with sideband suppressors, was stopped with an 0·16 cm aperture and placed 10·2 cm from the input end of the fibre to give a probe beam of 0·5° angular width. For this measurement the fibre length (47 m) was made relatively short to minimize

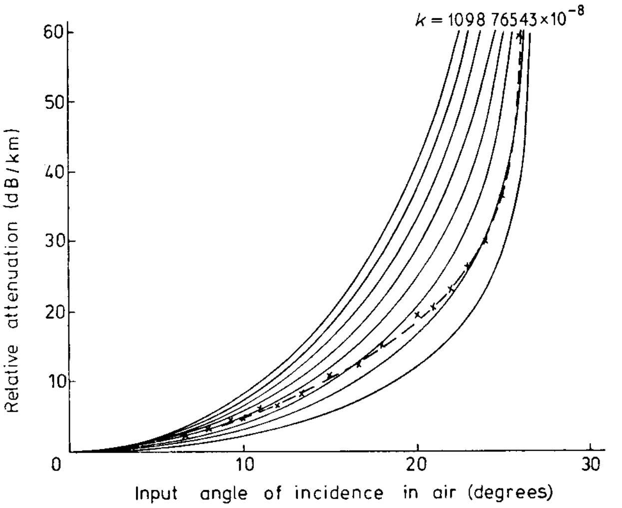

Fig. 1. Increase of attenuation of a probing beam as the angle of incidence on the fibre is increased. The solid lines are calculated for the values of k shown; the points are measured at 0·64 μm for a fibre of length 47 m and core diameter 38 μm.

the effects of mode conversion and the bend radius was 30 cm. For each value of θ the increase of transmission loss compared with the axial ray was measured and is indicated by the crosses in Fig. 1. For this method of launching most of the input power is launched in the form of skew rays so that equations (5a) and 5(b) are not directly applicable and a skew ray analysis must be used. This involves substituting in equations (5a) and (5b) the angle of incidence for a given skew ray, followed by integration over the appropriate energy distribution in the fibre (see Appendix). Curves for various values of loss coefficient k have been computed and are indicated by the solid lines in Fig. 1.

It can be seen that the ray attenuation rises relatively slowly for angles of incidence up to about 10° but increasingly sharply at larger angles particularly at about 25°. At small angles the experimental points lie along the $k = 6 \times 10^{-8}$ curve and move gradually to that for $k = 4 \times 10^{-8}$, the corresponding cladding attenuation values being 5000 dB/km and 3400 dB/km respectively. There will be some residual mode mixing present and other evidence[6] suggests that the effect will be more marked at smaller angles. Thus we feel that greater reliance should be placed on the attenuation deduced from large angle values, namely ~3400 dB/km.

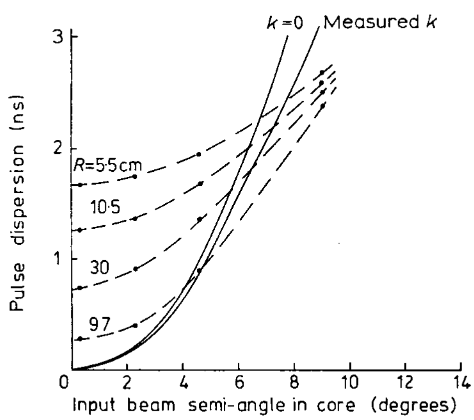

Fig. 2. Pulse dispersion as a function of beam angular width in the core for a fibre of length 180 m and core diameter 50 μm at 0·633 μm. The solid lines are calculated for the coefficients indicated and the points are measured for fibre coiled on drums of radii R shown.

The experimentally deduced values of k as a function of θ were now used in conjunction with equations (3), (4) and (5) to obtain output pulse shapes for the experimental length (180 m) of fibre for various angular widths of input beam. From the pulse half-widths the dispersions shown by the lower solid curve in Fig. 2 were plotted. For comparison the upper solid curve shows the dispersion calculated under identical conditions for the same fibre assumed to be lossless. It can be seen that the effect of cladding loss, and the resultant mode filtering due to preferential attenuation of higher-order modes (high-angle rays), is to cause a reduction in dispersion particularly in input beams of large angular width. It is not easy to make a direct comparison with experiment since the above theory assumes that the fibre is straight and that no mode conversion occurs. Experimental measurements are most conveniently carried out with the fibre coiled on a drum which can cause[6] mode conversion. Figure 2 also shows measured dispersions for the fibre wound on drums of different radii and it may be seen that at small angular widths the experimental results for increasing bend radius R_0 move asymptotically towards the theoretical curve. Unfortunately it has not been possible to lay out the fibre in a straight line in the laboratory.

At large angles the experimental dispersions are still less than those calculated for the lossy fibre and the reason for this is not certain. However, our tests have shown that the fibres from which the results were obtained were sufficiently tightly wound on the supporting drums to cause additional mode conversion, as shown by an increase in the angular width of the propagating rays.

Furthermore in a curved fibre the energy distribution is not symmetrical about the axis, as required by the analysis, but is displaced outwards and this will have an effect on the measured dispersion.

Another possible explanation is that the cladding loss is higher than that indicated by the probing beam experiment. However, further computations indicate that in order to obtain agreement at large angles with experimental dispersions extrapolated to a straight fibre it would be necessary to invoke a cladding loss of 20 000 dB/km. In fact α_k has also been measured by an independent method. Firstly, the ME1 tubing is drawn in such a way that a solid-core fibre is formed. The attenuation of this unclad fibre is then measured by hanging it horizontally and without supports along its length. The results are given in Fig. 3 and show that at 0·633 μm the loss is 2030 dB/km.

This method measures the average loss over the crosssection of the fibre whereas the probing beam indicates the loss of the internal surface layer of the liquid-filled ME1 tube which could be rather different. However, both results indicate that the cladding loss is more likely

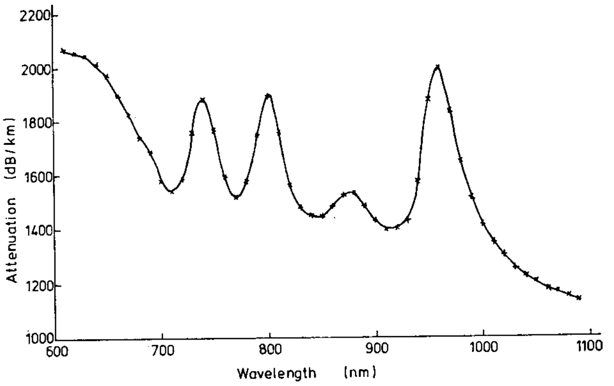

Fig. 3. Loss of unclad ME1 fibre.

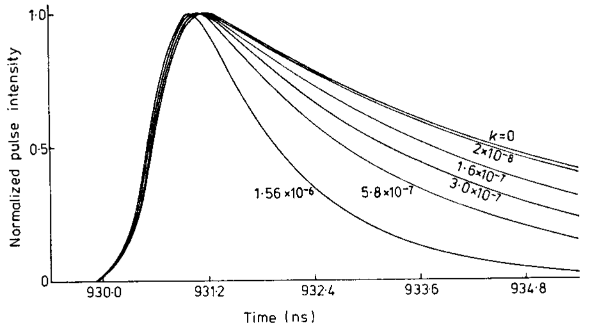

Fig. 4. Variation of output pulse shape with cladding loss coefficient at 0·633 μm for a fibre of length 180 m and core diameter 50 μm. The beam width in the core is ±8° and the Gaussian input pulse is of half-width 0·65 ns.

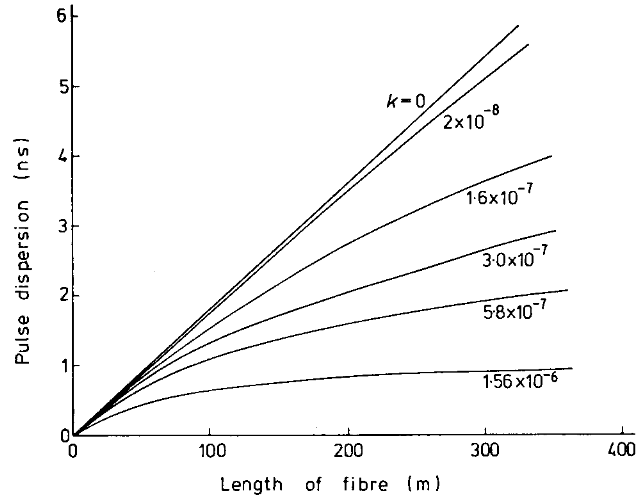

Fig. 5. Variation of pulse dispersion with length for various values of cladding loss coefficient at 0·633 μm for a fibre of core diameter 50 μm and a beam width in the core of ±8°.

to be in the region of 2–3000 dB/km rather than 20 000 dB/km, which in itself is surprising since ME1 is a sealing glass and is not intended for optical use. The low experimental dispersion for input beams of large angular width therefore cannot be completely explained in terms of high cladding loss. Nevertheless, the theory is in qualitative agreement with experiment and may be applied to the case of unstressed fibres with reasonable confidence.

5 Effect of Cladding Loss on Dispersion

Having examined the influence of cladding loss on dispersion for a particular fibre it is of interest to investigate the effect more broadly. The core loss largely determines the overall fibre attenuation but, as shown above, has little effect on dispersion for attenuations at least as high as those discussed here. Figures 1 and 2 clearly illustrate the mode filtering action and Fig. 2 also shows how the dispersion can depend on bending of the fibre. The computations have been repeated for a range of k values and Fig. 4 shows that with increased cladding loss the effect on the output pulse shape is marginally to sharpen the leading pulse edge and to shorten considerably the trailing edge. This is because the rays which are first to reach the output are those travelling at small angles to the axis and are thus least affected. As may be concluded also from Fig. 2 the pulse broadening in our liquid-core fibre, for the length and launching conditions shown, is roughly four-fifths that of an equivalent lossless fibre at an input angular width of ±8°.

The calculated variation of pulse dispersion with fibre length, Fig. 5, confirms earlier results that in a straight lossless fibre, and in the absence of mode conversion, the pulse width varies linearly with length. However, in the presence of cladding loss, when mode filtering takes place, the curves have a characteristic shape consisting of an initial rise which gradually becomes a broad maximum followed by a steady fall (for lengths greater than those shown in the figure). The length at which the maximum occurs falls with increasing cladding loss and, as the theory also shows, with smaller core diameters. A comparison of the results obtained for different angular widths of the input beam indicates that for small lengths and cladding losses the dispersion is predominantly controlled by the launching conditions while for longer lengths and high cladding loss it is the latter which is the determining factor. The dispersion thus becomes a non-linear function of length and we obtain the interesting result that the differential pulse dispersion can be made zero or even negative, as the higher-angle rays are progressively removed. A method therefore seems to be available for selecting a desired fibre dispersion or bandwidth, for a given length, by appropriate choice of cladding loss, core diameter and launching conditions.

Mode filtering occurs because of the penetration of the electromagnetic field into the lossy cladding, the depth of which is determined by the refractive index difference. We have accentuated the magnitude of the effect by substituting tetrachloroethylene, having a refractive index difference of 1·501 at 0·633 μm, for the core liquid and using a Pyrex cladding, of refractive index 1·475 and loss $\sim 2\times 10^5$ dB/km. The numerical aperture was thus changed from 0·45 to 0·28 and this enabled the non-linear variation of dispersion with

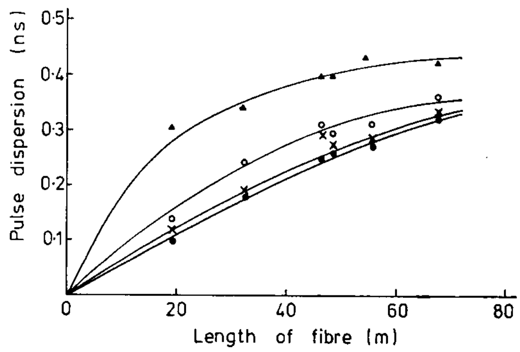

Fig. 6. Variation of pulse dispersion with length for various angular beam widths in the core as follows: △ 9·3°; ○ 4·83°; × 2·5°; ● 0·5°. The fibre consisted of tetrachloroethylene in Pyrex tubing of internal diameter 63 μm. The radius of curvature of the fibre was 5·5 cm.

length to be observed even in short lengths of fibre, as in Fig. 6. For an input beam width of 9·3° the pulse width is approaching a maximum at a fibre length of about 70 m. The measurements given in Fig. 6 are thus also in (qualitative) agreement with theory.

6 Effect of Cladding Loss on Total Attenuation

Although cladding loss can increase the bandwidth of a fibre it is important that the resulting increase in total attenuation should not be unacceptably high. There are two forms of attenuation which must be considered, namely (i) c.w. attenuation due to absorption and scattering, and (ii) peak pulse reduction due to dispersion. A normal attenuation measurement gives a value for the former which also describes the effect on total pulse energy. However, in a pulse-modulated communication system the detector normally responds to pulse height which suffers a reduction due to both absorption and dispersion of energy. As discussed above, and shown in Fig. 4, the cladding loss attenuates mainly the trailing edge of the pulse and has only a small effect on the pulse height, producing very little peak pulse reduction.

The contribution of the cladding to the c.w. transmission loss of our liquid-core fibres is only 1 or 2 dB/km at the most[11] yet it has a significant effect on the dispersion. If the cladding loss were to be increased to, say, 20 000 dB/km ($k = 3 \times 10^{-7}$) then for an input beam of angular width ±8° Fig. 5 indicates that the dispersion would be ~3 ns for a 0·4 km length compared to 7 ns in a lossless fibre and, because of the non-linear dependence with length, the relative difference is much greater over a kilometre. Thus the zero-loss dispersion would be 18 ns at 1 km compared with 5 ns for a 20 000 dB/km cladding.

Figure 7 shows that under the same conditions the contribution of the cladding to the c.w. fibre attenuation would be 3·6 dB for a 0·4 km length and less than 8 dB perhaps as little as 5 dB, over 1 km. This is small considering the large change in dispersion. The change in peak pulse height due to the cladding is, of course, small. An input beam of smaller angular width would experience a smaller attenuation and a corresponding lower dispersion. In fact, the cladding attenuation could be tailored to match the source used and the bandwidth and attenuation desired.

Figure 7 also shows that the attenuation per metre depends on the length over which it is measured as well as the width of the input beam and both should therefore be specified when a fibre loss is quoted. The loss falls with increasing length as the higher-angle rays are progressively removed by the cladding.

Summarizing, therefore, if a conventional detector is used, and in the absence of mode conversion, the output pulse height is not appreciably reduced by increasing the cladding loss. However, even in the lossless case the pulse energy has been dispersed so that the output pulse height is reduced although there is no loss of energy.

7 Conclusions

A theory for propagation in lossy multimode optical fibres has been developed and used in the interpretation of experimental results obtained in fibres having a high-loss cladding. At large beam angles the measured dispersion is less than that predicted by theory, possibly due to mode conversion related to distortion of the fibre on the supporting drums.

It is shown that providing the core loss is not excessively large it has little effect on dispersion. The cladding loss has been obtained using a probing beam technique giving a value of ~3400 dB/km which is in reasonable agreement with that found by measuring the attenuation of the ME1 tubing drawn down into an uncladded fibre. In the presence of cladding loss the dispersion is reduced for a relatively small increase in c.w. attenuation. Both dispersion and c.w. attenuation become non-linear functions of length. While the presence of cladding loss reduces the total pulse energy the pulse amplitude is little changed.

In a fibre with zero mode conversion it has been shown that the presence of cladding loss reduces the dispersion caused by rays launched at large angles to the axis. In this relatively simple case a similar result could also be

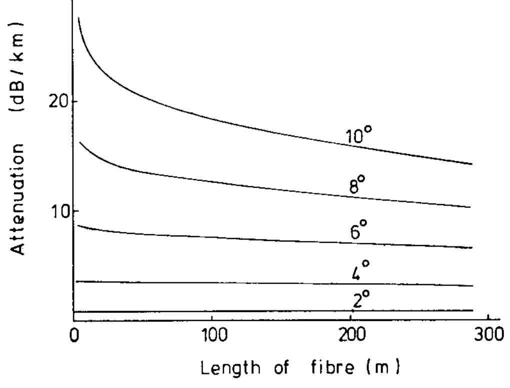

Fig. 7. Contribution of cladding loss to total fibre attenuation for the beam widths in the core shown on the curves, and for the relatively large cladding loss coefficient of 3×10^{-7}: (20 000 dB/km) at 0·633 μm. The core diameter is 50 μm.

achieved by the use of apertures[7] at the input or output or, where possible, by changing the numerical aperture of the fibre. Since each ray travels at a constant angle to the axis a better technique would involve some form of equalization of propagation times so as to reconstitute the input pulse with no loss of energy. A possible method has already been suggested.[12] In a practical fibre the situation will be complicated by mode conversion due to bends, scattering and inhomogeneities. In normal fibres where mode conversion may have a significant but not dominant effect over lengths of practical interest, cladding loss can be used to reduce the dispersion at a modest cost in attenuation of total pulse energy. On the other hand, instead of counteracting mode conversion an alternative approach[13] is to enhance it in a highly-controlled manner so as to cause a sufficient scrambling of rays (modes) over practical lengths that they have the same propagation time for any launching angle. The hazard of this approach is that rays 'converted' to angles greater than that corresponding to the numerical aperture are coupled into the cladding and constitute a loss. Whether a practical low-loss mode scrambling technique can be developed remains to be seen.

Finally, it must be commented that the ray analysis progressively fails as the number of propagating modes becomes small. The more correct modal analysis[14] must then be used.

8 Acknowledgments

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10 Appendix: Reflexion Loss of a Probe Beam Injected into a Fibre at angle θ

A generalized skew ray analysis may be used[15] to determine the additional fibre attenuation caused by a high-loss cladding, but the numerical integration required is complex. Considerable simplification can be made in the case of a plane wave of uniform intensity entering the fibre core at an angle θ to the axis.

Each of the two symmetrical halves of the input cross-section of the core are divided into j ($j = 1, 2, \ldots m$) incremental strips of width $h = d/2m$ parallel to the plane of incidence of the input beam. For unit power incident on the core the power P_j on each of the jth strips is

$$P_j = 1 + \frac{8}{\pi d^2}\left[jh\left\{\left(\frac{d}{2}\right)^2 - (jh)^2\right\}^{\frac{1}{2}} - \left(\frac{d}{2}\right)^2 \cos^{-1}(2jh/d) - (P_{j-1} + \ldots P_2 + P_1)\right] \tag{6}$$

where $P_j = 0$ for $j \leqslant 0$.

All rays contained within the jth strip propagate down the fibre successively reflecting from the core/cladding interface at the same angle to the interface ξ_j, given by

$$\xi_j = \sin^{-1}(\cos\beta_j \sin\theta) \tag{7}$$

where

$$\beta_j = \sin^{-1} 2(j-1)h/d$$

The loss at each reflexion is found by substituting ξ_j for θ into equations (5a) and (5b), while the number of reflexions made by rays contained within this strip is $L \tan\theta/d \cos\beta_j$.

Finally, the total transmitted power $P(\theta)$ is found by numerical integration over all strips,

$$P(\theta) = \sum_{j=1}^{m} P_j R(\xi_j)^{\frac{L \tan\theta}{d \cos\beta_j}} \tag{8}$$

from which the cladding induced loss in dB/km for an injection angle θ follows.

The effect of the cladding on the total fibre attenuation may be found by angular integration over a particular input distribution, weighted by results such as those shown in Fig. 1 for the loss as a function of angle.

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