4th ECOC, Genoa, 1978.

LOSS MECHANISMS IN PRACTICAL SINGLE-MODE FIBRES

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Abstract
Detailed studies have been carried out on propagation in practical single-mode fibres and especially of those factors causing a rise of attenuation due to radiation. A new theory of loss caused by mode conversion is proposed and is applied to the problem of microbending. The factors which must be taken into account during cable manufacture are discussed.

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1. Introduction

Single-mode fibres have several potential advantages when considered for long-distance communications, in particular that bandwidths of tens of GHz can be achieved over tens of kilometres limited only by material and mode dispersions. Coupling to integrated optical circuits is also easier than with multimode fibres and furthermore they are easier to use in couplers. Recent attention, however, has been mainly focussed on multimode fibres.

One of the main disadvantages of the single-mode fibre is the small core diameter which makes jointing and launching into the fibre difficult. Accurate methods for measuring the core diameter 2a and the refractive index Δn between the core and cladding are needed. Conventional techniques for measuring the core diameter of a multimode fibre cannot be used because of the effects of diffraction since the core diameter is of the order of a wavelength. Once Δn and a are known the normalised frequency V and the numerical aperture,NA, can be calculated. The NA of a fibre is a very important factor in propagation studies since it strongly affects the radiation loss which increases as the NA decreases.

Fabrication of single-mode fibres [1] has been made comparatively simple but some problems still remain. For example the refractive-index profile of a single-mode fibre may not be a perfect step but may have a dip at the centre or there may be grading of the core/cladding boundary due to diffusion of the dopants. The influence of the dip and grading of the profile on wave propagation is important but many studies of single-mode fibres, including some methods for determining the characteristics of the fibre, assume a stepped refractive index.

The transmission loss of a fibre can be influenced by radiation due to curvature and microbending. The radiation loss at bends arises from two different mechanisms [2,3] namely the pure-bend loss and transition loss. The pure-bend loss occurs because at a certain distance from the centre of curvature the local phase velocity equals the velocity of light and guidance ceases so that energy is radiated. The transition loss, on the other hand, is due to mode conversion as the mode of the straight fibre transforms to that of a curved fibre. Extensive studies [2,3] have been carried out on these two mechanisms and it is found that both must be considered in calculations of loss due to uniform curvature and also of micro-bending loss. This last result is important as hitherto theories of microbending loss have only considered mode conversion and have neglected the pure-bend loss.

67

Finally, it is shown that the loss of the LP_{11} mode is very high near its cut-off point and fibres having V values up to 3 can be used for single-mode operation.

2. Characterisation of Single-Mode Fibres

2.1 Measurement of fibre parameters

For any type of fibre two of the fundamental parameters are the core diameter a and the relative refractive-index difference $\Delta = (n_1 - n_2)/n_2$ between the core (n_1) and the cladding (n_2). From these two parameters the normalised frequency V is defined as

$$V = (2\pi a/\lambda)(n_1^2 - n_2^2)^{\frac{1}{2}} \sim (2\pi a/\lambda)(2n_2^2\Delta)^{\frac{1}{2}} \qquad \ldots (1)$$

For multimode fibres the core diameter can be measured by conventional optical techniques. However this is not possible with single-mode fibres as the core diameter is comparable to a wavelength and diffraction makes measurements difficult.

One method has been suggested [4] whereby the normalised cut-off frequency of the 2nd higher-order mode is measured by bending the fibre. However it has been shown [5] that this method gives an effective value of V which is much higher than the actual cut-off frequency. This is because microbending in the fibre can produce a high loss of the LP_{11} mode just above its cut-off frequency which increases the effective value of V. In practice we have observed single-mode operation in even short lengths of fibre having V=2.8.

A simple method has been found [6] for determining a and Δ from the measurement of the far-field pattern at a single wavelength. The far-field distribution can be calculated from the Fraunhofer diffraction equation [7] and the approximate field equations derived by Snyder [8].

It can be shown from theory, as well as experimentally, that in addition to the main beam the far-field pattern has several subsidiary lobes. The ratio $\sin\theta_x/\sin\theta_h$, where θ_x is the angular width to the first minimum and θ_h is the output angle at which the intensity has fallen to half of its central maximum, is an unambiguous function of V. Hence measurement of this ratio enables V to be determined. It can also be shown [6] that another unambiguous function of V is

$$\alpha_h = ka\sin\theta_h \qquad \ldots (2)$$

Therefore by using the value of V obtained from the ratio $\sin\theta_x/\sin\theta_h$ and eqn. (2) the core radius a can be calculated. With a and V known Δ can then be found from eqn. (1), where α_h is now the normalised half-intensity angle.

2.2 Spot size of the HE_{11} mode

Another important parameter of a single-mode fibre is the spot size of the HE_{11} mode since this largely determines the coupling efficiency and the jointing loss due to misalignment. A simple definition of mode spot size has been suggested [9,10,11]. In the single-mode region and for V>2.0 the excitation of the HE_{11} mode by a Gaussian beam is greater than 99%. Therefore the spot size of the HE_{11} mode is defined as that of the input Gaussian beam which gives maximum excitation efficiency [12]. It should be noted that this simplified definition of spot size differs from the width to 1/e intensity of the HE_{11} mode in the core but gives good agreement with that of Reference 13 especially for V>2.0, the difference between the two values being less than 1% at V=2.4.

3. The Effects of Departures from a Stepped Refractive-Index Profile

So far it has been assumed that the single-mode fibre has a rectangular index distribution. However in practice a dip in the profile at the centre of the core and grading of the profile at the core/cladding interface will occur. These effects are due to preferential evaporation of the more volatile component during the preform-collapsing stage and diffusion at the core/cladding interface. Both affect the guidance properties, increase and change the spot size of the mode.

The propagation of the HE_{11} mode in a single-mode fibre having a dip in the refractive-index distribution has been analysed [14]. The results show that the cut-off frequency of the single-mode region increases as the degree of dip increases. A factor G is therefore proposed, which defines the "degree of guidance" of a fibre and can be used to estimate the cut-off frequency of a fibre with any refractive-index distribution. G is defined by

$$G = \int_0^a \frac{\varepsilon(r) - \varepsilon_2}{\varepsilon_1 - \varepsilon_2}\, r\,dr \text{ so that } V_c = 2.4(2G)^{-\frac{1}{2}} \qquad \ldots (3)$$

As mentioned above, the method for the determination of a and V [6] assumes that the fibre has a step-index profile and the effect on the far-field radiation pattern of a dip must be considered. For larger dips the radiation angle becomes smaller but otherwise the far-field pattern is almost the same as for a step-index fibre. Hence the theory for a step-index fibre is still applicable.

The effect of the dip on the validity of the definition of mode spot size given in section 2 is also important as with a dip present the near field is somewhat different from Gaussian in shape. The excitation efficiency has been calculated as a function of input spot size for various depths of dip and it is found that the optimum input spot size changes but an excitation efficiency of more than 97.6% can still be achieved. The definition in terms of a Gaussian beam is therefore still a reasonable approximation of the HE_{11} mode spot size.

The effect of grading of the profile on the propagation characteristics of a single-mode fibre has been considered in reference 10. It is found that, as in the case of a dip in the core centre, the normalised cut-off frequency increases as the degree of grading increases. However for $\alpha>50$ the grading of the index has little effect on V_c.

The normalised spot size of the HE_{11} mode varies with α and is in general larger than that for a step-index fibre at small V and smaller for large V. Comparison of the mode spot size using the more accurate definition [13] with the simplified definition for $\alpha=2$ gives a good agreement and we are therefore justified in using the simple definition.

4. Bends in Single-Mode Fibres

The transmission loss of single-mode fibres can be increased by the radiation loss due to bending. It has been observed [15] that radiation emitted in the transverse direction at the beginning of a bend is not continuous but appears in the form of discrete divergent rays. Measurement of the radiated intensity in the plane of a bend shows that the intensity distribution is oscillatory at the beginning of the bend with peaks corresponding to the ray radiation.

Miyagi and Yip [16] have calculated the transition loss ($2P_R$) due to coupling between the guided modes of the straight fibre and the radiation modes at the beginning and end of the curved section of fibre and have shown the total transmission loss (Γ_t) to be given by

$$\Gamma_t = 2P_R + 2\alpha_c L \qquad \ldots (4)$$

where L is the length of curved fibre and $2\alpha_c$ is the pure-bend loss per unit length. On the basis of this equation the transmission loss can be illustrated schematically by the straight line A in Fig.1. However in practice the power coupled to the radiation field is not lost instantaneously, as evidenced by the ray radiation. In addition the mechanical stiffness of the fibre prevents an abrupt change of curvature. Therefore, intuitively one might expect the transmission loss to be of the form shown by curve B in Fig.1. At the beginning of the bend the transmission loss increases gradually and is oscillatory because of coupling between the guided HE_{11} mode and the radiation modes; this region is called the transition region. After a certain point the loss becomes uniform and increases linearly with bending angle; this region is the pure-bend region.

Both the transition loss and the pure-bend loss can be obtained by measuring the loss as a function of transmission distance. Fig.1 shows that the transition loss is given by the intersection of the linear portion of the curve with the ordinate, while the pure bend loss can be obtained from the slope.

The transmission loss has been measured by progressively wrapping a fibre around a drum of diameter 2R. The results are shown in Fig.2 for drums of different diameters. It is seen that the form of the curves is the same as that suggested in Fig.1. In the transition region the loss is oscillatory but for convenience a smooth curve has been fitted to the data. The transition loss and pure-bend loss can be obtained from Fig.2 and for small lengths of bend, the transition loss exceeds the pure-bend loss [2].

4.2 Mode coupling theory and equivalent radiation mode

In this section we outline the theory used to calculate the transition loss due to mode coupling between the guided HE_{11} mode and the radiation modes.

A curved fibre may be represented, through a conformal transformation, by an equivalent straight fibre where the curvature distribution is accounted for by an equivalent refractive index distribution in the straight fibre [17] given by

$$n_e = n_{1,2}\left[1 + (r/R)\cos\theta\right] \qquad \ldots (5)$$

where (r,θ) are circular coordinates, R is the radius of curvature of the fibre, which is generally a function of distance, and $n_{1,2}$ is the refractive index of the core, cladding.

By applying mode coupling theory to this equivalent straight fibre an expression for the transition loss due to coupling between the guided HE_{11} mode and the radiation modes can be derived. Integration over θ shows that only coupling between the guided HE_{11} mode and the radiation modes with $\mu=\pm 1$ takes place. This theory is developed in reference 3 and the transition loss P_r is derived as

$$P_r = 2\left(\frac{L}{a}\right) A(U,W) \int_{-kn_2 a}^{kn_2 a} B(X) F^2(L,X)\, dX \qquad \ldots (6)$$

where $A(U,W)$ is a function of U and W; $U^2 + W^2 = V^2$; $B(X)$ is the coupling coefficient, and $F(L,X)$ is the distortion function. First consider an abrupt change of curvature between the straight and curved sections of fibre. The power density of the radiation modes for this condition is calculated for $V=2.4$, $\Delta=0.0005$, $L/a=400$ and is shown in Fig.3. It is found that the radiation power varies non-uniformly with βa where β is the propagation constant of the radiation modes. Only the radiation modes having propagation constants close to kn_2a contain any appreciable power. The power density for the backward waves is negligible.

Using the mode coupling theory the power in the radiation modes has been calculated as a function of normalised fibre length (L/a) and is shown in Fig.4 for the fibre parameters given above. The radiation power is an oscillatory function of distance indicating that part of the radiation mode power is coupled back into the HE_{11} guided mode. At longer distances a steady-state value is reached. The results have been compared with existing theories. The solid line in Fig.4 is calculated using the simplest loss formula derived in reference 18 and the dotted line is calculated using the theory derived by Miyagi and Yip [19]. These two results are near the steady-state value of the oscillatory radiation power and we can therefore infer that they only give the loss at large distances from the junction. It is therefore important to consider the contribution of the radiation modes over short lengths because part of the power which they contain can be coupled back into the guided mode.

Two important parameters can be derived [3]. These are the power weighted mean value of the propagation constants for the radiation modes ($X_e=\beta_e a$) and the r.m.s. deviation from that mean (σ_r). The average propagation constant of the radiation modes, β_e, varies periodically with the fibre length. The weighted r.m.s. deviation σ_r is small which means that there is only a narrow spectrum of radiation modes. Hence the radiation modes behave as a quasi-guided mode with propagation constant β_e. If we call the quasi-guided mode the $R(\beta_e)$ mode the ray radiation can be simplified by considering coupling between the HE_{11} mode and the $R(\beta_e)$ mode and the power oscillation can easily be understood [20,21]. Fig.3 shows the power-weighted average propagation constant β_e of the radiation modes and it is seen that it is close to kn_2.

The parameter $(\beta_o-\beta_e)a=(X_o-X_e)$, see Fig.3, is an important one. It can be shown [3] that each peak in the radiation power of Fig.4 corresponds to a minimum value of $(\beta_o-\beta_e)$ and at the same time the r.m.s. spread of propagation constants of the radiation modes is a minimum. Therefore at each peak in the radiated power the radiation is approximately coherent and the various modes emerge in the same direction which is in agreement with the rays observed experimentally [15].

4.3 Loss for a gradual change of curvature

The above calculations assume an abrupt change of curvature but in practice this will not occur. We therefore consider the change in curvature to occur over a length π/b. By varying the value of b we can vary the sharpness of the bend. For an abrupt junction $\pi/b=0$. We can again calculate the transition loss due to this curvature by using the mode-coupling theory and the results are shown in Fig.5 as a function of normalised radius of curvature for various normalised lengths π/ab. The fibre parameters are $V=2.4$, $\Delta=0.0005$ and $L/a=2100$.

We must consider the pure-bend loss in such bends which, in a fibre of length L and having radius of curvature R(z), may be found from eqn. (20) in reference 3. Using this equation we have calculated the pure-bend loss as a function of the radius and rate of change of curvature. Fig.5 shows that for small bending radii the pure-bend loss exceeds the transition loss. However there is a "cross-over radius" at which the transition loss predominates, in agreement with the experimental result of section 3. For larger π/ab, i.e. for more gradual transitions, the transition loss decreases considerably but the pure-bend loss is only slightly changed, hence the cross-over radius increases. We can therefore conclude that even at large bend radii the pure-bend loss may be greater than the transition loss and therefore calculations of microbending loss which only consider mode conversion may not be valid.

4.4 Bending loss in cables

The contribution to the overall transmission loss in fibres due to cabling may be quite large if sufficient care is not taken. A common method of cabling fibres is to wrap the fibre in a helix around a central strength member. If the pitch of the helix is too small a high bending loss may result.

The bend radius R of a fibre of overall diameter d which is wrapped in a helix around a central strength member of diameter D' is [22]

$$R = Rm\left[1+\left(\frac{P}{2\pi Rm}\right)^2\right] \text{ where } Rm = \frac{d+D'}{2}\text{; P is the pitch of the helix} \quad \ldots (7)$$

Using this equation and the pure-bend loss theory the pitch of the helix which gives losses of 1dB/km (solid lines) and 2dB/km (dashed lines) is shown in Fig.6. The fibre parameters are V=2.4, a=4.05μm, d=0.2mm. Obviously the limiting pitch depends strongly on both the diameter of the strength member and the NA, hence both must be carefully chosen to keep the loss low.

5. Microbending in Fibres

Besides the radiation loss caused by bends in the fibre, as discussed above, microbending loss due to axis deformation also occurs. From the mode coupling theory the transition loss of a fibre due to random deformation can be calculated by taking the ensemble average of the Fourier spectrum of the distribution function. In practice the type of deformation is not known and therefore two particular cases will be considered.

Case 1 $\quad S(u) = 2\bar{\sigma}^2\exp(-u^2/D^2)$ ...(8a)

and

Case 2 $\quad S(u) = 2\bar{\sigma}^2\exp(-u/D)$ ...(8b)

$2\bar{\sigma}^2$ is the variance of $1/R(z)$ and D is the correlation length. It is assumed that $\langle 1/R(z)\rangle=0$ and hence $\sqrt{2}\sigma$ is the r.m.s. deviation.

The normalised microbend transition loss $P_n = P_r/\{(\sigma a)^2(L/a)^2\}$ is shown as a function of D/a for various Δ in Fig.7. The solid and dotted lines refer to cases (1) and (2) respectively. The most important point to note is that the maximum value of the transition loss is virtually independent of the correlation function, as also is the loss for values of D/a below the maximum. The loss is a strong function of Δ, because (X_o-X_e), defined in section 4.2, increases as Δ increases [3]. Hence coupling from the HE_{11} mode to the radiation modes becomes progressively weaker with increasing Δ and a fibre of large NA will exhibit low values of microbending loss as well as bending loss.

The above discussion only considers the transition loss component of microbending loss but for most cases the pure-bend loss must also be allowed for as it forms a large contribution to the total radiation loss. Under some conditions the pure-bend loss can be much greater than the transition loss [2,3].

5.2 Loss due to a single microbend

We now consider the effect on the transmission loss of the fibre caused by a single microbend. Olshansky [23] has derived a formula for the curvature of the fibre due to a microbend:

$$\frac{1}{R(z)} = 2k^2h(\sin|kz| - \cos|kz|)\exp(-k/z) \qquad \ldots (9)$$

where $k = (g/2\pi E_f)^{\frac{1}{4}}(1/b)$, h is the height of the microbend, g is a constant which depends on the Young's modulus of the encapsulating material, b is the diameter of the fibre and E_f the Young's modulus of the fibre.

By using this form of curvature the pure-bend loss and transition loss have been calculated as a function of h for various fibre diameters. The results are shown in Fig.8 for bk=0.2 and V=2.4. The solid lines show the transition loss and pure-bend loss for NA=0.1, indicating that the pure-bend loss is greater than the transition loss for micro bends higher than 15μm. For comparison the transition loss for NA=0.06 is shown by the dashed lines.

Calculations for different values of bk show that the loss decreases rapidly as bk decreases, because a material with a lower Young's Modulus will exert a smaller restoring force of the fibre and a more gradual bend results. The loss also depends strongly on the fibre diameter and the NA, increasing as these two parameters decrease. From these calculations it can be seen that both the pure-bend and transition loss components must be considered in calculations of the microbending loss.

6. Single-mode Operation for V>2.4

Recent studies on propagation of the LP_{11} mode have shown that its loss, as it nears its cut-off point, is very sensitive to slight bends and pressure applied to the fibre. For example, bend radii of 3.2cm and 1.6cm at V=3.0 and NA=0.1 give losses of 3dB/cm and 50dB/cm, respectively, while the loss of the HE_{11} mode and mode conversion between the HE_{11} and the LP_{11} mode are negligibly small. It has been found that fibres with V<3.0 have a radiation pattern which is indistinguishable from that of a single-mode fibre after a length of only 1 metre so that single-mode operation can be obtained in practice at relatively high V values.

As shown in section 3 the cut-off value of the LP_{11} mode increases if the index profile is graded and we can therefore expect single-mode operation for values of normalised frequency as high as V=5. The advantage of having a higher value of V is that either the core radius or the NA of the fibre can be increased. As we have already shown the radiation loss depends strongly on NA. Therefore by using a fibre with a larger NA the radiation loss can be decreased considerably.

7. Conclusions

In this paper we have considered various aspects of propagation in single-mode fibres. A method for measuring the V value and core radius of the fibre by measurement of the far-field pattern of the HE_{11} mode has been described. This method, however, assumes that the fibre has a step-index profile which is usually not the case. We also give a simplified definition for the mode spot size of the HE_{11} mode in terms of the Gaussian beam which gives maximum excitation efficiency.

The effect of a graded-index profile, and of a dip in the centre of the profile, on wave propagation has been considered. It is found that both cause the V value of the fibre to increase, which is to be expected since the guidance factor of the core decreases. However unless the grading or dip effects are very severe, there is little difference between parameters calculated assuming a step-index profile and those calculated using the exact profile.

The radiation loss in a fibre due to curvature and microbending has been studied and is found to comprise two components, namely a transition loss and a pure-bend loss. Both of these mechanisms are found to contribute to the uniform curvature and microbending losses. It is therefore important to consider both mechanisms in any estimation of attenuation due to bends.

A theory has been developed for calculating the transition loss due to coupling between the HE_{11} guided mode and the radiation modes. It is found that the radiation modes can be represented by a single quasi-mode with propagation constant β_e. Using this modified coupling theory the transition loss due to an abrupt change of curvature has been calculated as a function of fibre length and is found to be oscillatory at the beginning of the bend as observed experimentally. We can therefore consider the transition loss as being due to coupling between the HE_{11} mode and the quasi radiation mode. With increasing distance along the curved fibre the radiation loss approaches a steady state value. A continuous change of curvature between the straight and uniformly bent fibre reduces the transition loss considerably. It is found that for longer lengths of the continuous region the radius of curvature at which the pure-bend loss exceeds the transition loss increases.

The pure-bend loss due to helical bending of the fibre which will occur due to the lay of fibres in cables has been calculated. It is found that the lay length must be carefully chosen to keep the loss at a low value.

The transition loss due to microbending has been considered by using a Gaussian type of autocorrelation function. It is found that the maximum transition loss is almost independent of the type of autocorrelation function used. Both the pure-bend loss and the transition loss contribute to the overall loss of a single microbend, the pure-bend loss being greater than the transition loss for larger bumps. The loss depends strongly on the Young's modulus of the encapsulating material, the diameter of the fibre and the NA.

Finally it is shown that single-mode operation is still possible for V values as large as 3 for a step-index fibre and 5 for a graded-index fibre. This has the advantage that the NA can be increased and hence the radiation loss will be decreased.

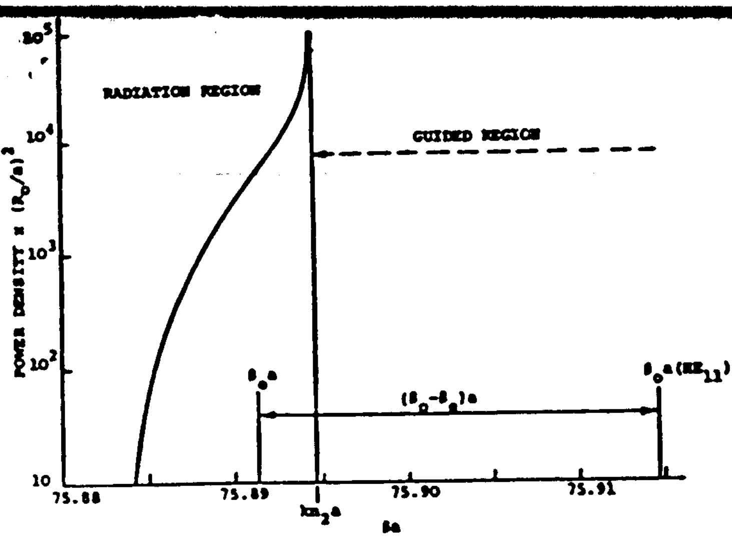

Fig. 3 Radiation mode power versus βa

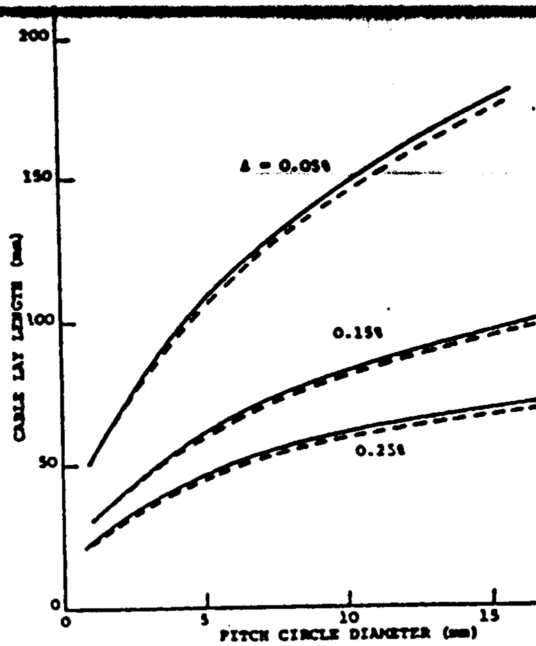

Fig. 6 Limiting cable lay length for constant bend loss versus pitch circle diameter

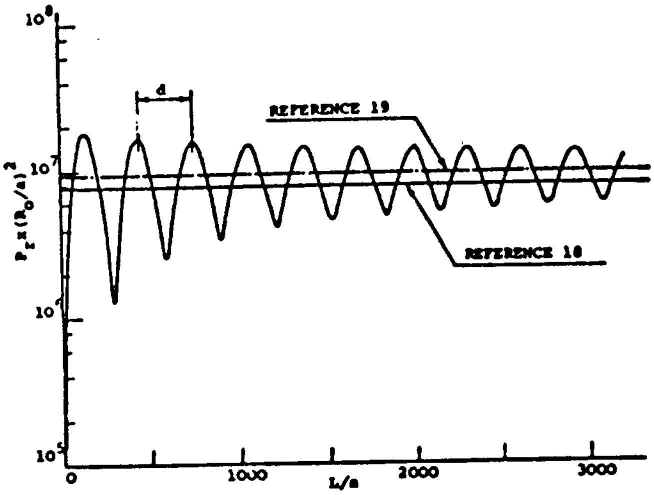

Fig. 4 Total radiation power versus distance

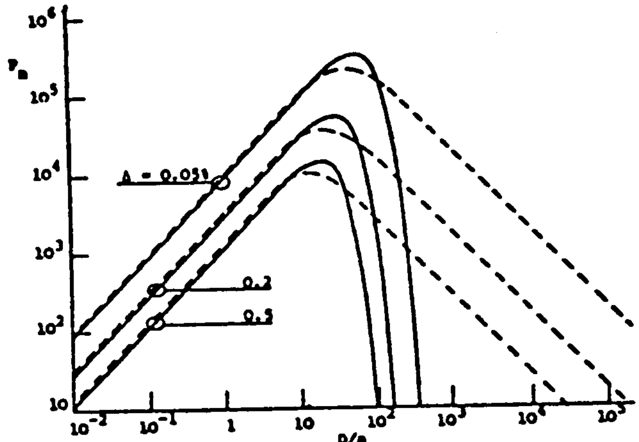

Fig. 7 Transition microbend loss versus correlation length

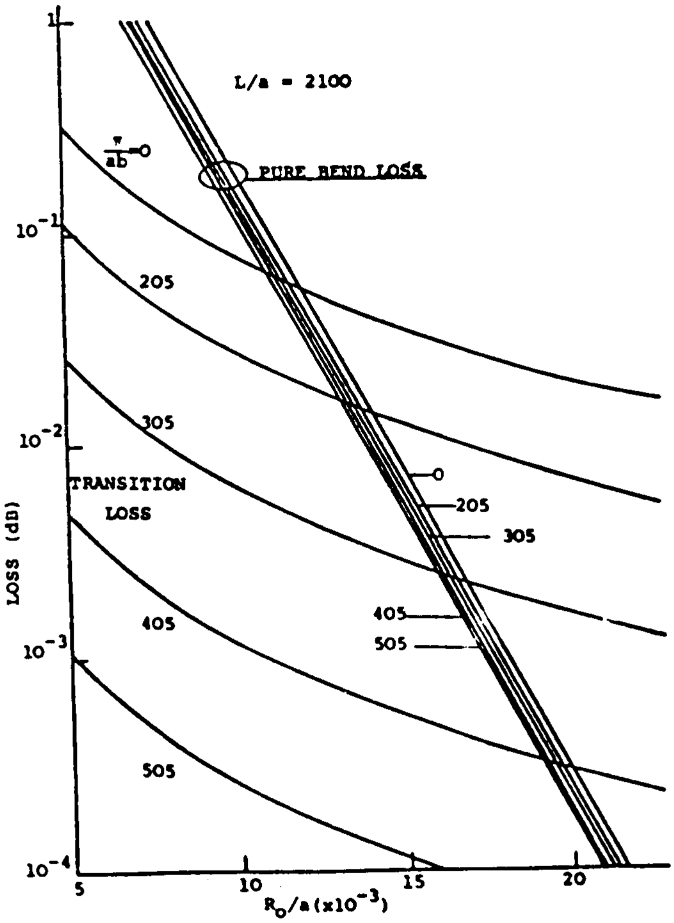

Fig. 5 Transition and pure-bend loss for different curvatures

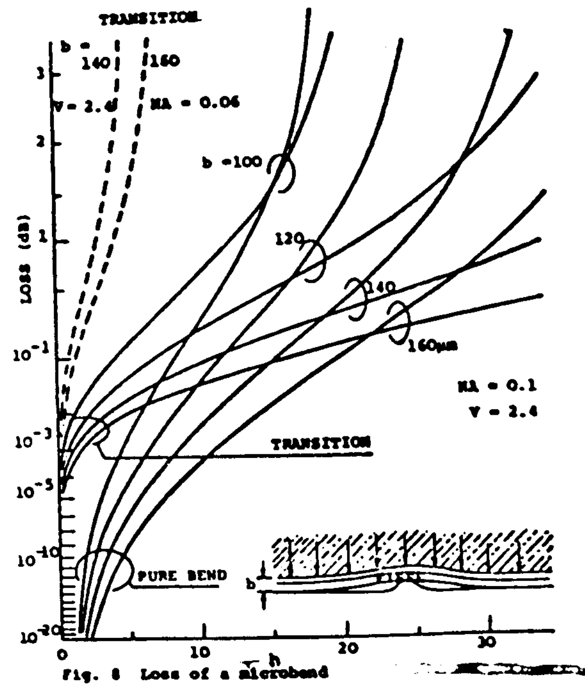

Fig. 8 Loss of a microbend

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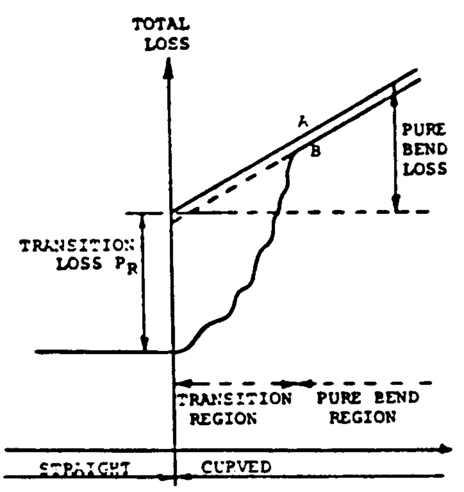

Fig.1 Loss near start of bend

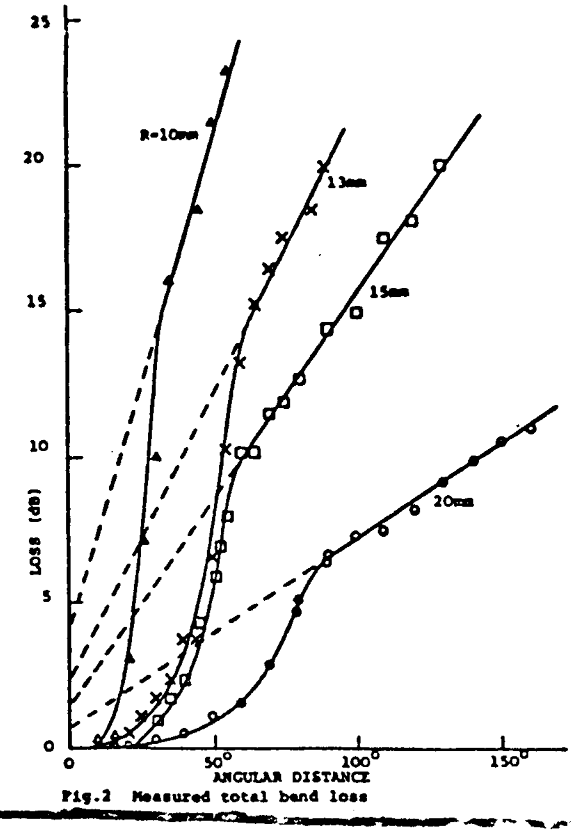

Fig.2 Measured total bend loss