Bend loss in large core multimode optical fiber beam delivery systems

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We present results of an experimental investigation of the optical losses produced by bending large core optical fibers, typical of those used in power beam delivery systems. Experiments have been conducted over a range of core diameters for both plastic clad silica and all-silica fibers as a function of bend radius. A theoretical model has been developed for predicting the magnitude of the bend loss, and agreement was obtained with the experimental results. The study thus yields design information for fiber beam delivery systems. *Key words:* Fiber optics, bend loss, Nd:YAG beam delivery.

I. Introduction

Since the advent of fiber optics it has been recognized that when fibers are bent optical losses are produced.[1] Bend loss has received considerable attention chiefly because of its adverse effect on the power budget in fiber optic systems, especially in telecommunications.[2] However, the phenomenon has also been usefully exploited as a means of sampling the power guided in a fiber without interrupting it[3] and as a transduction mechanism in fiber optic sensors.[4]

Our motivation in the work presented here was to understand bending loss in fibers used for the delivery of optical power from Nd:YAG lasers, especially for materials processing applications. The objective was to develop design information for fiber optic beam delivery systems used for this purpose, where recognized advantages[5] include the ability to straightforwardly scan the workpiece, to situate the laser remotely (especially for operations in hazardous or inaccessible locations), and to distribute power from a single central laser to a number of workstations. Bend losses are particularly serious in high power applications where power wastage may be significant, and may cause thermal damage to the fiber or its cable, with an attendant risk to safety.

Bend loss has been the subject of detailed studies, notably for telecommunications systems.[6] Such results cannot be directly applied for power beam delivery systems which use fibers of much greater core diameter (⩾200 μm) and shorter length (typically 5–50 m). The larger core size is necessary to reduce power densities and hence the risk of fiber damage (especially at the entrance face). Also, Nd:YAG lasers used typically for materials processing have low spatial coherence (i.e., low beam quality) and hence can be coupled efficiently only into larger core fibers.

When light is coupled into arbitrarily long fibers, the process of mode coupling causes the power to be distributed among the guided modes with an equilibrium distribution. This equilibrium is assumed in most theories of bend loss. However, this assumption cannot be used for the relatively short fibers used in power beam delivery. Although mode coupling still occurs, it does not reach equilibrium, so that the power distribution among the modes is dependent on the properties of the source and the launch optics, as well as on the distribution of bends along the fiber.

We developed existing theory so that bend loss can be predicted as a function of the properties of the fiber (core size and numerical aperture) and the bend (radius and length), without assuming an equilibrium modal distribution. We conducted bend loss experiments with a wide range of different step index multimode optical fibers with different bend conditions. In each case, the power distribution in the fiber was measured and used as an input to the theoretical model. Good agreement was obtained between the theoretically calculated and experimentally determined bend losses. We have therefore developed a design model for considering bend loss in fibers used for power beam delivery.

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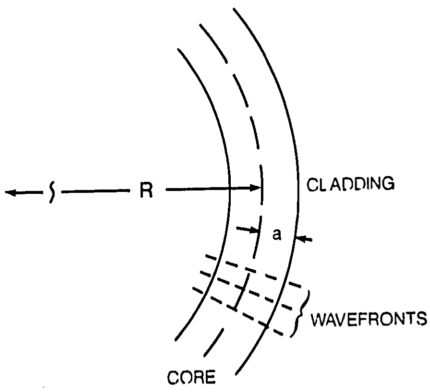


Fig. 1. Curved Fiber: R, bend radius; a, core radius.

II. Theory

The problem of bending losses from waveguides has received considerable theoretical study by a number of authors. A general method has been developed by Marcuse,[7,8] who computed the electric and magnetic fields at a large distance from the curved waveguide, and thus found the radiated Poynting vector. From the radiated power per unit length, an effective attenuation coefficient is determined. A simplified derivation for this attenuation coefficient, actually for the more straightforward analogous case of the curved slab waveguide, is given by Marcuse.[9] A general introduction to the subject of curved waveguides is given by Lewin *et al.*[1]

An exhaustive reference list for bending losses would be very lengthy, but representative selections of approaches are described by Miller and Talanow,[10] Marcatili,[11] Lewin,[12] Arnaud,[13] Snyder *et al.*,[14] Schevchenko,[15] and Chang and Kuester.[16] Schevchenko[15] has developed the arguments of Marcatili and Miller,[17] later refined by Gloge,[18] to produce an approximate result in a form which renders computation straightforward for the present purposes. We shall therefore adopt this approach, which is summarized briefly below.

For a straight and unperturbed fiber, the electric field of the guided beam decays exponentially into the cladding to form the evanescent wave. When the fiber is bent, the phase velocity of the wavefront around the outside of the bend must be greater than it is in the cladding, as shown in Fig. 1. The velocity of propagation increases as we move farther away from the core, until it becomes equal to the local velocity of light. At this point the wave is no longer guided and is radiated off.

This model shows that the power loss attenuation coefficient of a guided mode propagating at an angle θ to the axis for a step index fiber is given by[18]

$$\alpha = 2n_1k\,(\theta_c^2 - \theta^2)\exp\left[-\frac{2}{3}n_1kR\left(\theta_c^2 - \theta^2 - \frac{2a}{R}\right)\right]^{3/2}, \qquad (1)$$

where n_1 is the refractive index of the fiber core, k is the propagation constant ($k = 2\pi/\lambda$, where λ is the free space wavelength of the light), θ_c is the critical angle (i.e., the maximum value of θ for guided modes in the unperturbed fiber), a is the radius of the fiber core, and R is the radius of the bend measured to the axis of the fiber.

This model is an extension of the result given by Schevchenko[15] which deals with small radiation loss and large bend radius. According to Gloge[18] this model may only be applied to higher-order modes which travel near critical angle θ_c. The mechanism of the power loss is due to the cutoff of the higher modes, which means the bend reduces the effective numerical aperture of the fiber. The loss rises sharply near angle

$$\theta_f = \theta_c\left(1 - \frac{2a}{R\theta_c^2}\right)^{1/2}, \qquad (2)$$

and hence all the modes beyond this angle are effectively lost. As can be seen, when R is sufficiently large, $\theta_f \simeq \theta_c$. We may hence state that the power in guided mode $P(\theta)$, identified by its angle of propagation θ, after propagating a distance l around a bend is given by

$$P(\theta) = P_0(\theta)\exp(-\alpha l), \qquad (3)$$

where $P_0(\theta)$ is the power in mode θ at the entrance to the bend. To find the total power transmitted by the bend we sum over all modes. Because the number of modes is so great, we may replace the summation by an integration such that

$$P = \int_0^{\theta_f} P_0(\theta)\exp(-\alpha l)d\theta. \qquad (4)$$

The proportion of optical power lost as a result of propagation around the bend is thus

$$P_r = \left[\int_0^{\theta_c} P_0(\theta)d\theta - \int_0^{\theta_f} P_0(\theta)\exp(-\alpha l)d\theta\right] \Big/ \int_0^{\theta_c} P_0(\theta)d\theta. \qquad (5)$$

We note that α is a function of known fiber properties and of the geometry of the bend. The function $P_0(\theta)$ depends on the properties of the fiber, the input laser beam, and the beam launching optics. It is thus necessary to obtain the function $P_0(\theta)$ to apply the theory. In the present work, $P_0(\theta)$ was found experimentally.

III. Experiment

The experimental arrangement used to obtain practical values of bending loss is shown in Fig. 2. The laser used was a pulsed industrial Nd:YAG laser supplied by Lumonics, model JK702 in a welder configuration. The system is capable of achieving 250 W of average output power and operates at a maximum frequency of 500 Hz with a minimum pulse width of 0.6 ms. The following laser operating parameters were used for all the experiments: repetition rate of 30 Hz, pulse width of 10 ms, pulse energy of 5 J, average output power of 150 W.

An optical wedge was used to split and attenuate the beam. One of the reflections is used as a reference for the laser power at the input of the fiber, using a diffuser and photodetector *PD*1; the power coupled into the fiber is typically 1.5 W.

The launching optics consists of a diaphragm used to control the input numerical aperture of the beam by altering the beam diameter; lens L1 focuses the beam

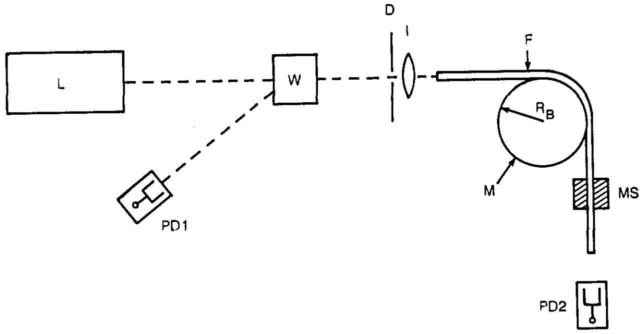


Fig. 2. Diagram of the experiment setup: L, Nd:YAG laser; W, beam splitting wedge; D, adjustable aperture; l, launching lens; F, optical fiber; MS, mode stripper; $PD1$ and $PD2$, photodetectors; M, mandrel of radius R_B.

into the fiber and can be used to change the beam spot size at the input face of the fiber. For all the experiments it was set to illuminate completely the numerical aperture of the fiber (i.e., 100% filling).

The fiber then follows a full turn around mandrels of different radii. Clamps were used to hold the fiber on the mandrel which has a smooth surface. When light is launched from a laser into a fiber, a proportion of the optical power is coupled into the cladding of the fiber. Similarly, light lost from the core of the fiber by the bend is ejected into the cladding. The cladding itself acts as a waveguide due to reflections either at the cladding–buffer or buffer–air interface. Over the relatively short lengths of fiber used in a beam delivery system and in our present experiments, a significant proportion of light in the cladding is guided to the output of the fiber. In beam delivery systems this is undesirable because the beam quality from the cladding light is lower than that for the core light. In the present experiments, cladding light reaching the detector leads to a serious underestimate of the bending loss.

For these reasons we employed a cladding mode stripper. This consists of a section of the fiber from which the buffer coating has been removed and which is immersed in a fluid having a refractive index very close to that of the cladding. Negligible reflection thus occurs at the cladding–fluid interface, so that light propagating in the fiber cladding is transmitted out into the fluid and is lost. Under some circumstances we noted differences of up to 3% in bend loss with and without the mode stripper. All experimental results reported below were obtained when using a mode stripper.

The output power from the fiber was monitored by a second diffuser and photodiode $PD2$. The outputs from the two photodetectors were linear with received power, and their ratio was determined using two independent lock-in amplifier channels and a ratiometer. The lock-in amplifier was triggered from the laser power supply.

To measure the bend loss, P_r defined by Eq. (5), the ratio of the photodetector outputs, $R_0 = P_2/P_1$, was first obtained with the fiber straight. The fiber was then bent to the required radius, and the new power ratio $R_1 = P_2'/P_1'$ measured. The experimental value of P_r is thus given by

$$P_r = (R_0 - R_1)/R_0. \tag{6}$$

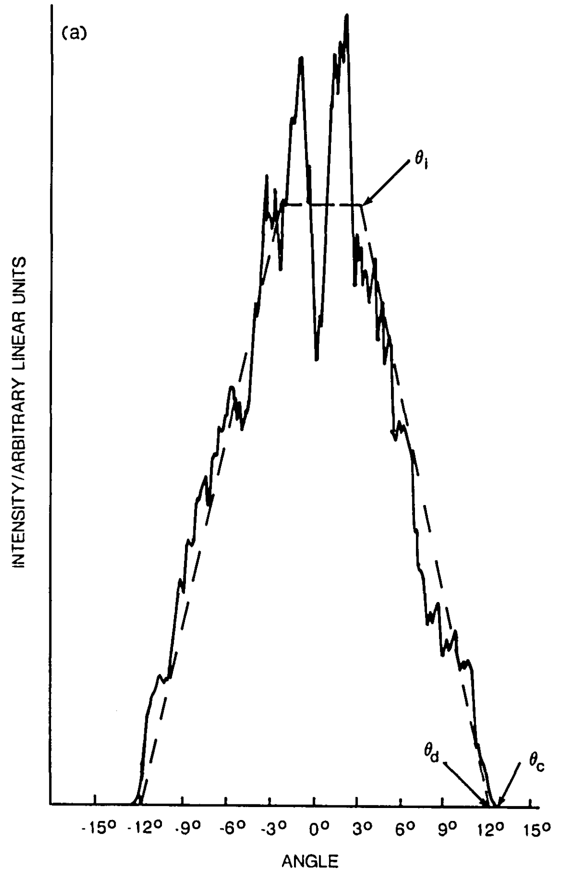
The power distribution function $P_0(\theta)$ was obtained from the far field intensity distribution of light emitted from the exit face of a fiber of a length equal to that between the input face of the fiber and the entrance to the bend in the bend loss experiments. This intensity distribution was found by scanning a 100-μm diam pinhole aperture across a diameter of the far field of the fiber and monitoring the power transmitted through the aperture using a linear photodetector. For the purposes of the present experiments it was sufficient to represent $P_0(\theta)$ by a trapezium function. Figure 3(a) shows a representative experimental plot for $P_0(\theta)$ obtained with a straight all-silica fiber of core diameter 600 μm and length 0.5 m, together with the best-fit trapezium. The vertices of the trapezium are defined by angles θ_i and θ_d which are expressed as fractions of critical angle θ_c.

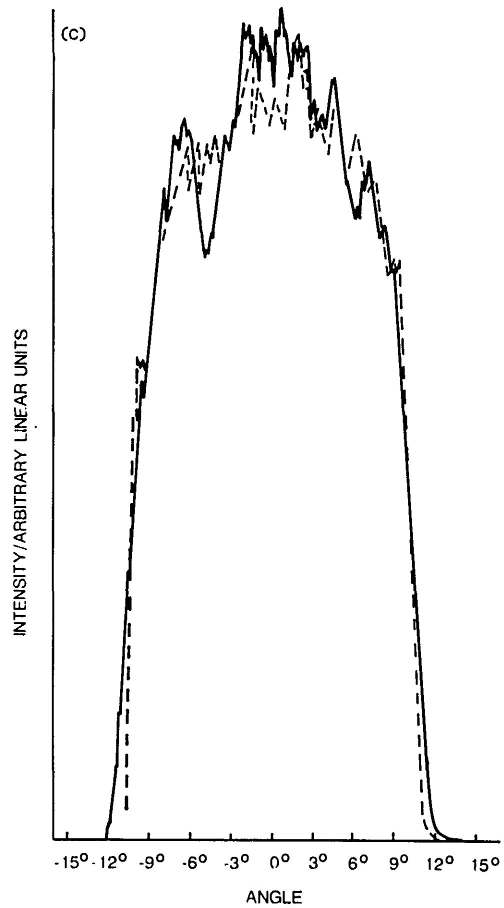
The importance of using the cladding mode stripper may be appreciated from Fig. 3(b) which compares the far field intensity distributions obtained with and without a cladding mode stripper. The critical angle for propagation in the cladding of the fiber used is greater than that for the core, and this is revealed by the extended wings in the distribution shown in Fig. 3(b).

IV. Results

Two types of multimode step index fibers with different numerical apertures and core sizes have been investigated. The first one was a hard polymer cladding fiber (HCS) with a numerical aperture of 0.37. The following core diameters was used: 200 μm 400 μm, 600 μm, and 1.0 mm. Each fiber had a length of 6 m. The second type was an all-silica fiber, i.e., with fused silica core and doped fused silica cladding, with a numerical aperture of 0.22 and core diameter of 600 μm with a length of 9 m. Both fibers are commercially available and widely used in high power laser beam transmission systems. Figure 4 shows the variation of bending loss with bend radius for different core sizes of the hard cladding fiber (HCS), using a fixed bend length and launch condition (100% filling). The graph shows how the loss increases significantly for a larger fiber core and reduced bend radius. Tight bends can produce excess losses of 2–3% which in a kilowatt delivery system may prove to be enough to damage the fiber. The experimental results are in agreement with the theoretical plots (solid lines), obtained from the input modal power distribution given by the far field output profiles.

The effect of a fiber numerical aperture is shown in Fig. 5, which gives the bending loss for the HCS and all silica fiber with the same core diameter (600 μm), bend length, and launching condition. The loss increases drastically for a reduced fiber numerical aperture.





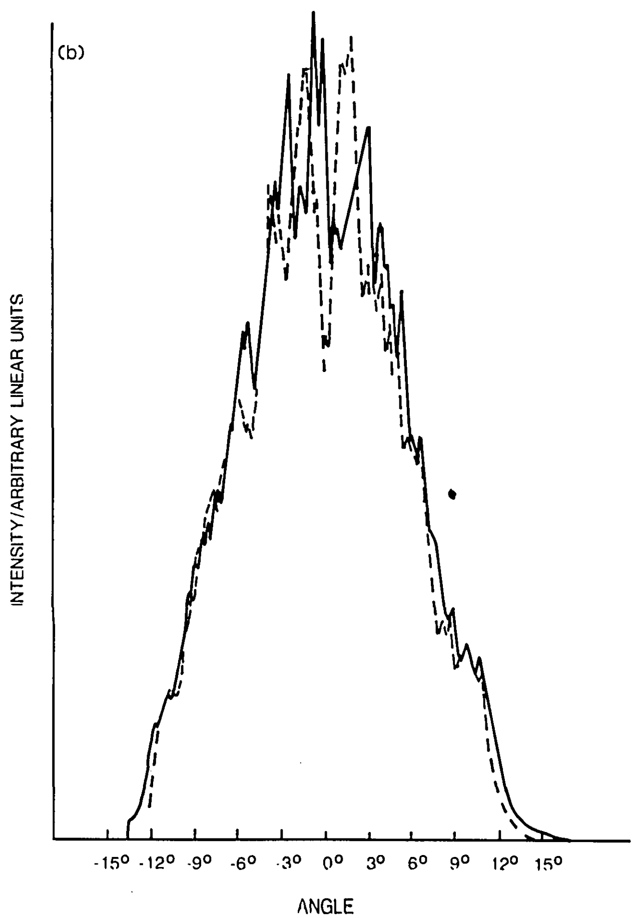


Fig. 3. (a) Far field intensity profile from an all-silica fiber with core diameter of 600 μm, numerical aperture of 0.22, and length of 50 cm, showing the trapezium fit, θ_i = 22% and θ_d = 95% of θ_c, where θ_c is calculated from the manufacturer's specification for the numerical aperture. (b) Far field profile showing the fiber with mode stripper (- - - -) and without mode stripper (—), in the conditions of (a). (c) Far field profile with a 6-m fiber length for the straight (—) and bent (- - - -) fiber, in the same conditions as (a).

Again good agreement is obtained between calculated and measured curves.

The effect of launching conditions on bend loss is presented in Fig. 6. The input beam numerical aperture has been reduced ($\theta_o < \theta_c$) resulting in an underfilled fiber. Therefore the $P_0(\theta)$ is underpopulated for higher values of θ, causing a reduction in bend loss.

Finally Fig. 3(c) shows how the bend modifies the output far field profile. A 600-μm core diam all-silica (N.A. = 0.22) fiber with 100% filling of the numerical aperture was used. The far field intensity profiles show the fiber in a straight configuration (solid line) and after a full turn around an 80-mm radius mandrel. The bend attenuates the higher-order modes (removed wings) and bend-induced mode coupling produces a slight broadening of the profile around the axis.

V. Discussion

Bend loss depends on bend radius, fiber parameters such as numerical aperture and core radius, and the launching conditions of the input beam. These factors must be taken into account when designing an optical fiber beam delivery system. As the numerical aperture of the fiber increases, the bend loss decreases, assuming other parameters to be fixed. On the other hand, increasing core radius will increase the bend loss. Part filling the fiber could dramatically reduce the bend loss in some circumstances but with the disadvantages noted below. A theoretical curve for loss vs fiber numerical aperture is given in Fig. 7 where the bend radius is 5 cm, the core diameter is 400 μm, and the filling condition is $\theta_d = 95\%\, \theta_c$, $\theta_i = 20\%\, \theta_c$. Figure 8 shows loss vs core radius where the numerical aperture is 0.3 and all the other parameters are the same as in Fig. 7. From these figures it can be seen that the general rule is to use optical fiber with the largest numerical aperture and smallest core consistent with power density and laser beam quality limits and restrict bends to the largest feasible radii. A comparison between 100% filled fiber, i.e., $\theta_i = \theta_d = \theta_c$, and a part filled fiber is given in Fig. 9, the conditions are bend radius 5 cm, numerical aperture 0.3, $\theta_i = 20\%\, \theta_c$ and $\theta_d = 95\%\, \theta_c$ for the part filled curve, and core diameter 400

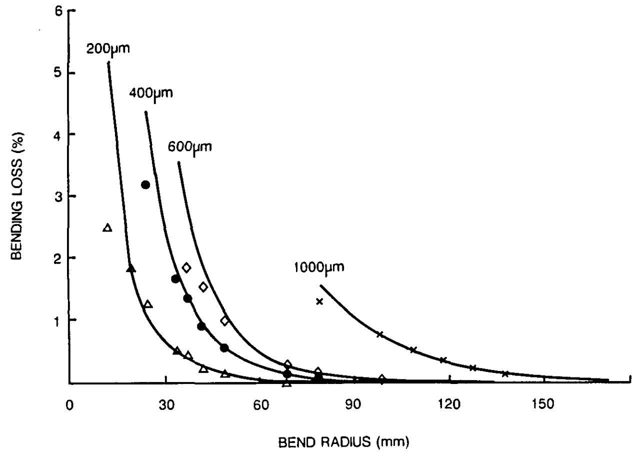


Fig. 4. Theoretical and practical bending loss as a function of bend radius and core diameter. HCS fibers with N.A. of 0.37, 100% filling $L = 6$ m, and core diameters of 200, 400, 600 and 1000 μm.

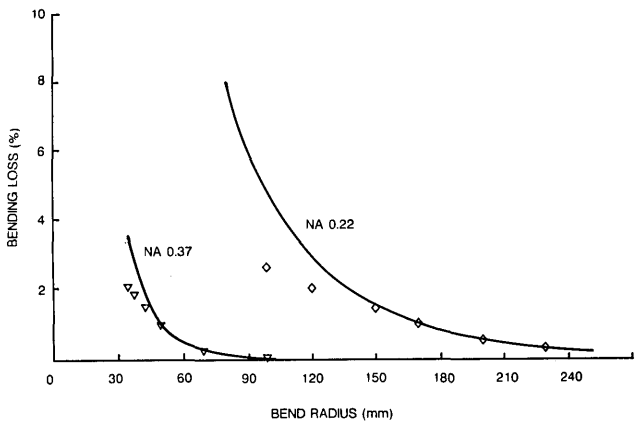


Fig. 5. Theoretical and practical bending loss for different fiber numerical apertures, fiber core diameter of 600 μm, $L = 6$ m, HCS N.A. = 0.37, and all-silica N.A. = 0.22.

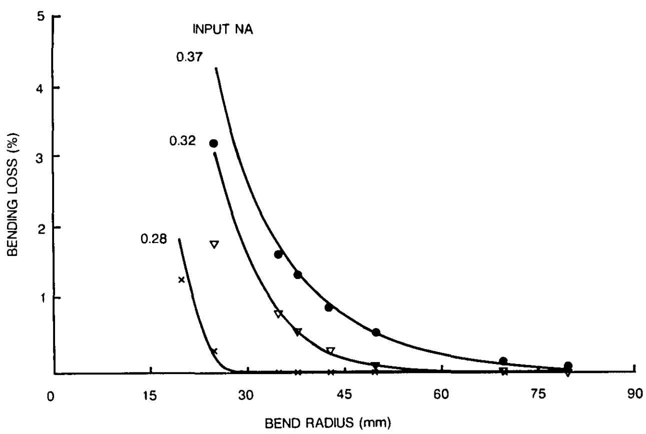


Fig. 6. Theoretical and practical bending loss variation with launching condition. HCS fiber with core diameter of 400 μm, $L = 6$ m. Input beam numerical apertures are 0.28, 0.32, and 0.37 (100% filling).

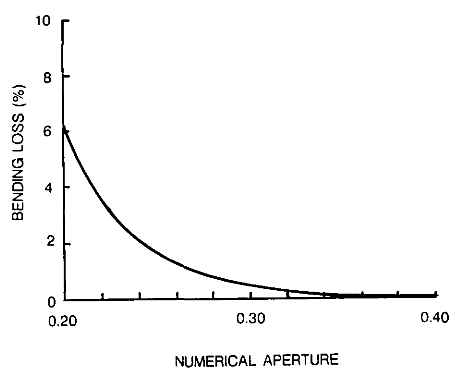


Fig. 7. Theoretical bending loss as a function of fiber numerical aperture with fiber core diameter of 400 μm and bend radius of 50 mm.

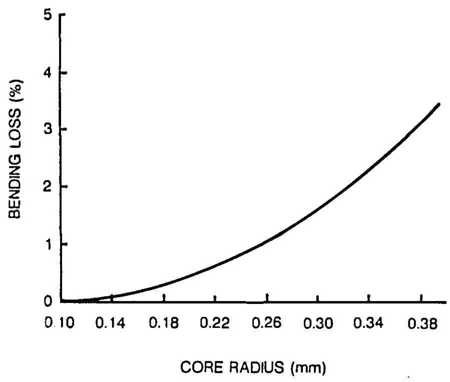


Fig. 8. Theoretical bending loss as a function of core radius with fiber numerical aperture of 0.3 and bend radius of 50 mm.

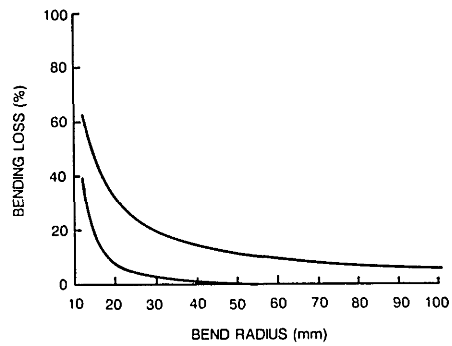


Fig. 9. Theoretical bending loss variation with fiber filling condition with fiber numerical aperture of 0.3 and core radius of 400 μm.

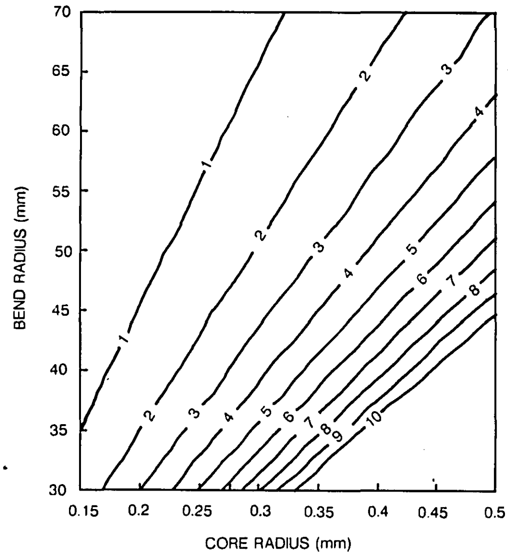


Fig. 10. Contour map of bending loss.

μm. For a given numerical aperture and filling conditions Fig. 10 shows the possible combination of bend radius and core radius to keep the loss below a given limit. Different limits are given as diffrent curves in the figure. The area above each curve represents the possible combination of bend radius and core radius to keep losses below the desired limit. The curve below ~3% loss gives a reasonable prediction, but beyond 3% the model predicts more loss than is observed experimentally, for reasons which are discussed later. However, since the theoretical model is pessimistic, it may be safely used for design purposes. Although underfilling fibers reduces the bend loss, it results in a degradation of the quality of the guided beam caused by mode coupling.[19]

We have noted that theory and experiment begin to diverge at small bend radii. However, such small bend radii are generally beyond the range of practical interest in the design of beam delivery systems and are often beyond the minimum bend radius specified by the manufacturer of the fiber. This divergence between theory and experiment is reasonable given that the model assumes that the bend radius is sufficiently large that the modes of the curved fiber are equivalent to those in the straight fiber. Furthermore, approximations required in the derivation of Eq. (1) assume that the loss is small.

The model assumes that the cladding is infinite. However, theoretical work on bend loss with monomode fibers with finite cladding has shown that light may be coupled back from the cladding into the core, thus reducing the net bend loss.[20] This phenomenon of recoupling has been corroborated by experimental evidence.

The theoretical model predicts a weak dependence of bend loss with length. We have seen that the attenuation coefficient α is a very strong function of propagation angle θ. Hence for $\theta > \theta_L + \delta$, α is very large and for $\theta < \theta_L - \delta$, α is very small; θ_L is a function of the fiber properties and the bend radius and δ is an arbitrary small angle.

Unless the fiber is very short, we may assume that all light with $\theta > \theta_L + \delta$ is completely attenuated; and that unless the fiber is very long all light with $\theta > \theta_L - \delta$ will experience negligible attenuation. Hence for bends of intermediate length, Eq. (5) becomes

$$P_r \simeq \int_{\theta_f}^{\theta_c} P_0(\theta)d\theta \Big/ \int_0^{\theta_o} P_0(\theta)d\theta, \tag{7}$$

which is independent of length.

The model does not explicitly account for the effects of mode coupling, although the experimental evidence in Fig. 3(c) shows that bending produces mode coupling, revealed by a change in the far field distribution.

It has been observed in unperturbed large core fibers that attenuation depends on mode and is increased for high-order modes. In our experiments this differential attenuation is accounted for by measuring $P_0(\theta)$ from the output of a straight fiber whose length is equal to that between the launching optics and the entrance of the bend in the bend loss experiments, and the bend loss measurement is made by comparing the power transmitted by a fiber when it is bent, as shown in Eq. (6).

VI. Conclusions

It has been shown that a relatively simple theoretical model may be used to design beam delivery systems in which bend losses may be reduced below 2–3%. The study confirms the importance of using large numerical aperture small core diameter fibers. It has also been shown that the launch optics significantly affect the bend loss and that the propagation of light within the cladding of the fiber may obscure the bend loss. The model fits experiment less well at higher losses. Although such losses are outside the range of most designs of beam delivery systems, they will be considered in future work. Bending affects the far field power distribution from a fiber as well as the total power. These mode coupling effects will be investigated further in the future.

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