

BEND – INDUCED LOSS IN A SINGLE – MODE FIBER

Aim

To study bend-induced loss in a single – mode fiber

Apparatus

Bread board, laser diode, laser diode aligner, microscope objective (20X), microscope objective holder, xyz-translational stage, photodetector with multimeter, photo-detector holder, two fiber chucks, two post bases and 3posts, a single-mode fiber (approx. 3m length), brass rods with circular cross section of different diameters (say, from 0.8 cm to 4 cm), razor blade, scotch tape, fiber cutter and index matching liquid.

Theory

Radiative losses occur whenever an optical fiber is subjected to extrinsic perturbations like bend of a finite radius of curvature [1-6], and such losses are called *bend loss*. An optical fiber can be subjected to two types of bends: (a) random microscopic bends of the fiber axis, for example, those that may occur when a fiber is sandwiched between two sand-papers, and (b) macroscopic bends having radii that are large compared to the fiber diameter, for example, those that may occur during cabling and laying of the fiber cable, respectively. Here, we are mainly concerned with the power radiated from single-mode fiber due to the latter type of bending, which is sometimes referred to as *macro-bending*. Any simple experiment that involves launching a laser light (e.g. from a laser diode) into a fiber that is first laid straight and then bent into an arc of a circle, would reveal that the fiber suffers radiation loss from the side at bends/curves along its path, which can be measured by measuring the drop in transmitted power with an optical power meter placed at the output end of the fiber – once laid straight, and then after introducing a bend in its lay.

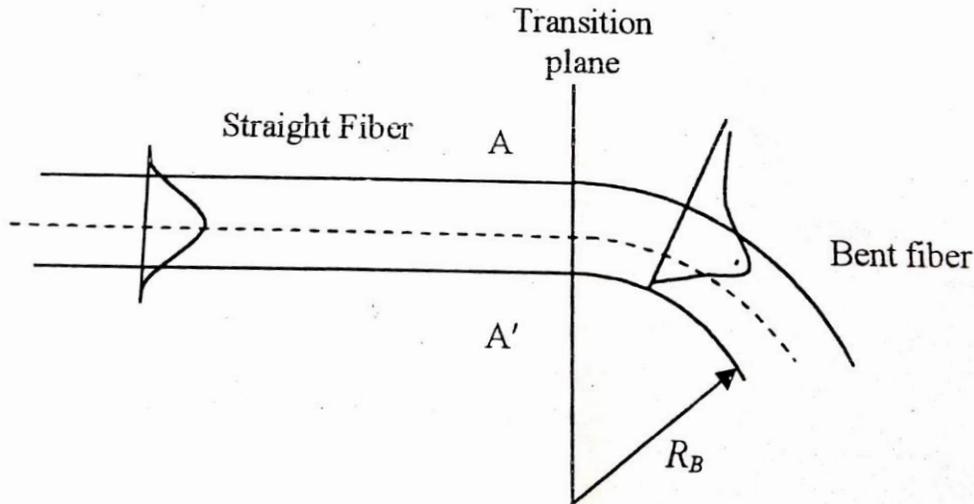


Fig. 7.1 A qualitative representation of the shift in the Gaussian-like fundamental mode away from the fiber axis at a bend.

For relatively small bends, this loss is extremely small and is essentially unobservable. As the radius of curvature decreases, transmission loss increases exponentially until at a certain critical radius of curvature when the loss becomes observable. If the bend radius is reduced below this threshold point, the loss suddenly becomes extremely large.

We first look at the physical process involved in the bending loss. A bend can be treated as a straight section of the fiber joined to a curved section of the fiber and joined again to another straight section, as shown in Fig. 7.1. According to the ray analysis, there are no truly bound rays in a bent optical fiber. Thus, every ray is leaky and radiated power through the mechanism of tunneling or refraction. For example, the *meridional rays* in a bent fiber are either tunneling rays or refracting rays, and skew rays lose power at successive reflections either through tunneling or refraction.

Qualitatively, the bending loss can be explained by examining the modal electric field distribution as shown in Figs. 7.1 and 7.2. The bending loss can be accounted for by the transition losses and the *macroband losses*. Transition loss is due to the abrupt changes in curvature occurring, e.g. at the cross sectional plane AA' of the

fiber shown in Fig. 7.1. The predominant effect of curvature on the fundamental mode is to shift the peak of the field distribution radially outwards (in the plane of the bend) by a distance r_d from the fiber axis as shown if Fig. 7.1. This shift, which is rather difficult to obtain exactly, within the Gaussian approximation of the field, is given as [2].

$$r_d = \frac{\beta^2 w_0^4}{2R_c} \quad (7.1)$$

where β is the propagation constant of the mode in the straight fiber, R_c is radius of Curvature of the bend and w_0 is the Gaussian spot-size [6].

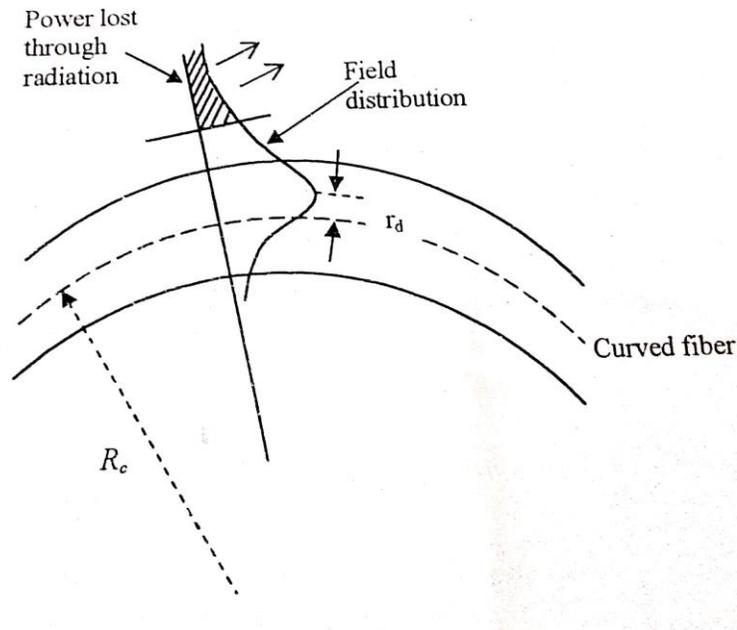


Fig. 7.2 Schematic representation of the bending loss in a section of fiber bent into an arc of radius R_c .

Thus the transition loss is due to the mismatch over the plane AA' between the fields of the straight section and the offset field of the curved section.

To get a feel for the numbers involved, let us consider a typical SMF with $n_1 = 1.46$, $n_2 = 1.457$ at an operating wavelength (λ_0) of 649 nm, and core radius $a = 2.1\mu\text{m}$, which yields $V \cong 1.90$. The corresponding Gaussian spot-size is calculated using the empirical relation [6].

$$w_0 = a \left(0.65 + \frac{1.619}{V^{3/2}} + \frac{2.879}{V^6} \right)$$

For the above SMF, $w_0 = 2.791 \mu\text{m}$. If we further assume that $\beta \approx \frac{2\pi}{\lambda^0} \left(\frac{n_1 + n_2}{2} \right)$, then for $R_c = 0.5\text{cm}$, one gets $r_d = 1.206 \mu\text{m}$. The transition loss is given by [6]

$$\alpha_t(\text{dB}) = 4.34 \left(\frac{r_d}{w_0} \right)^2,$$

And the corresponding transition loss turns out to be 0.81 dB.

The second mechanism of loss is the actual transmission loss suffered due to radiation from side of the bent fiber. We know that any bound (core) mode has an evanescent *tail* in the cladding, which decays almost exponentially with distance from the core-cladding interface [6]. Since the evanescent tail move along with field in the core, part of the energy of a propagating mode travels in the fiber cladding. In a straight fiber of arbitrary profile, the modal field at every point in the cross-section propagates parallel to the fiber axis with the same phase velocity, so that the planes of constant phase are orthogonal to the axis. However, if the fiber is bent into planar arc of constant radius, as shown in Fig. 7.2, it can be intuitively seen that the fields and phase fronts rotate about the center of curvature of the bend with constant angular velocity. Consequently, the phase velocity parallel to the fiber axis must increase linearly with the distance from the center of the curvature of the bend. Thus, the evanescent tail on the far side of the center of curvature must move faster to keep up with the field in the core. At a certain critical distance d_c from the center of the fiber, the portion of the evanescent tail (in the cladding) would have to move faster than the speed of light in the fiber cladding to keep up with the core field. Since this is not possible as per fundamental laws of nature namely constancy of light's speed in a given medium, the optical energy in the evanescent tail beyond d_c radiates away [3]. Close to and within the core, the fields are accurately described by a local mode, provided the radius of curvature is sufficiently large.

The pure bend loss coefficient (in dB per unit length of the bent fiber) in a single moded step index fiber is given by [1]:

$$\alpha \approx 4.34 \left(\frac{\pi}{4aR_c} \right)^{\frac{1}{2}} \left(\frac{U}{VK_1(W)} \right)^2 \frac{1}{W^{3/2}} \exp \left[-\frac{4}{3} \frac{R_c}{a} \frac{W^3 \Delta}{v^2} \right] \quad (7.2)$$

Where, a is the core radius of the fiber, R_c is the radius of curvature of the bent fiber, $K_1(x)$ is the modified Bessel function of second kind. The parameters U , W , V and Δ are defined through.

$$U = \sqrt[3]{k_0^2 n_1^2 - \beta^2}$$

$$W = \sqrt[3]{\beta^2 - k_0^2 n_2^2}$$

$$V^2 = U^2 + W^2$$

$$\Delta \cong (n_1 - n_2)/n_2$$

and

$$k_0 = 2\pi/\lambda_0$$

It should be noted that in evaluating the above expression, the quantities $-\lambda_0$, a and R_c must have the same units, e.g. centimeters (cm). For the fiber parameters considered above, one gets $V \cong 1.90$, $U \cong 1.49$, $W \cong 1.18$, $K_1(W) = 0.45$, which yields $\alpha = 51.52\text{dB/cm}$ when $R_c = 0.5\text{cm}$. One can also calculate the transition loss, which is usually much smaller than the pure bend loss.

In the experiment, a few turns are given to the fiber so that the loss is measurable and then α is calculated as follows:

$$\alpha = -\frac{10}{L} \log \frac{P_2}{P_1} \quad (7.3)$$

Where L is the length of the fiber (within the bend) i.e. $2\pi R$ x (no. of turns), P_1 is the output power without the bend in the fiber and P_2 is the output power with the bend in the fiber.

Procedure

Figure 7.3 shows the schematic of the set-up for the measurement of the macrobending loss in a single-mode fiber. For this, following procedures have to be followed step by step.

1. Mount the laser diode in the aligner and adjust with the help of the aligning screws.
2. Ends of a single-mode fiber of approximately 3m in length are prepared so that it has well-cleaved ends.
3. The cladding modes are removed by applying an index matching liquid (e.g. liquid paraffin) over a few centimeters of the bare fiber, near both the input and output ends and then clamped over the fiber chucks/holders. One end of the fiber is held in the xyz- translational stage and the other in a V-groove that is mounted on a post base.,
4. Light is launched from the laser diode using a 20X-microscope objective into the fiber.
5. The output end of the fiber is coupled to the photodetector, connected to the multimeter to measure the amount of light transmitted through the fiber. The multimeter reading is then noted down. This is P_1 , power without the bending around the brass/aluminum rod. Now to measure P_2 i.e. the output power with the bending around the brass rod, following steps have to be carefully followed.
6. Fiber is clamped with cello tape at a distance 1 m from the input end (as shown in Fig. 7.3 at A) as well as just before the output end as (shown in Fig. 7.3 at B). In this way we would be having approximately 2 m length of the fiber in between the clamped point A and B.
7. Exactly between the clamped points, a smooth brass/aluminum rod of uniform cross section is fixed as shown in the set up and fiber is wound over it. For the brass rods of diameters between 2 to 4 cm, 10 to 20 turns (or more, to achieve significant difference between P_1 and P_2) of the fiber are wound on the rod. Whereas, for the brass rod having diameters from 1 to 2 cm you may choose suitable number of turns between 1 and 10. Between A and B, the fiber segments on the either side of the rod should be stretched straight, bearing the same tension.
8. Vary the bending loss by changing the rods of different diameter and winding the fiber with suitable number of turns over it. Each time, note down the multimeter reading corresponding to the output of the detector.

9. Calculate the losses in dB per unit length using Eq. 7.3 and plot the measured loss as a function of the bending radius.

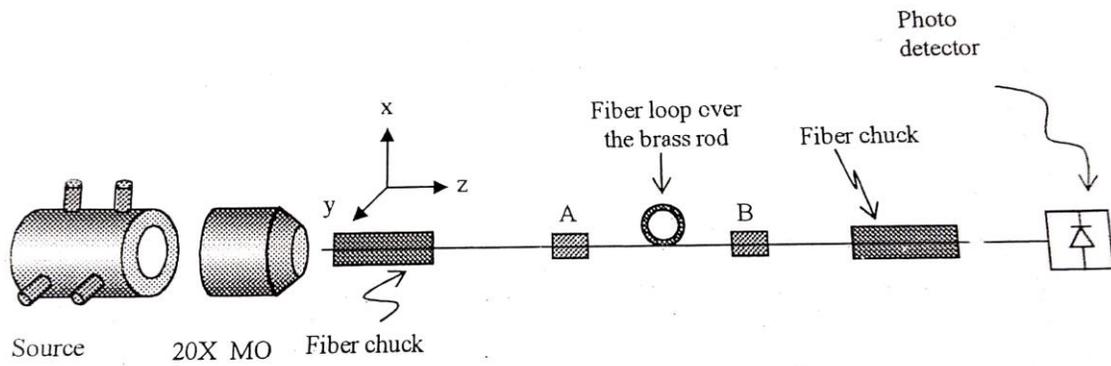


Fig. 7.3 Experimental setup to study the macrobending loss in a single mode fiber

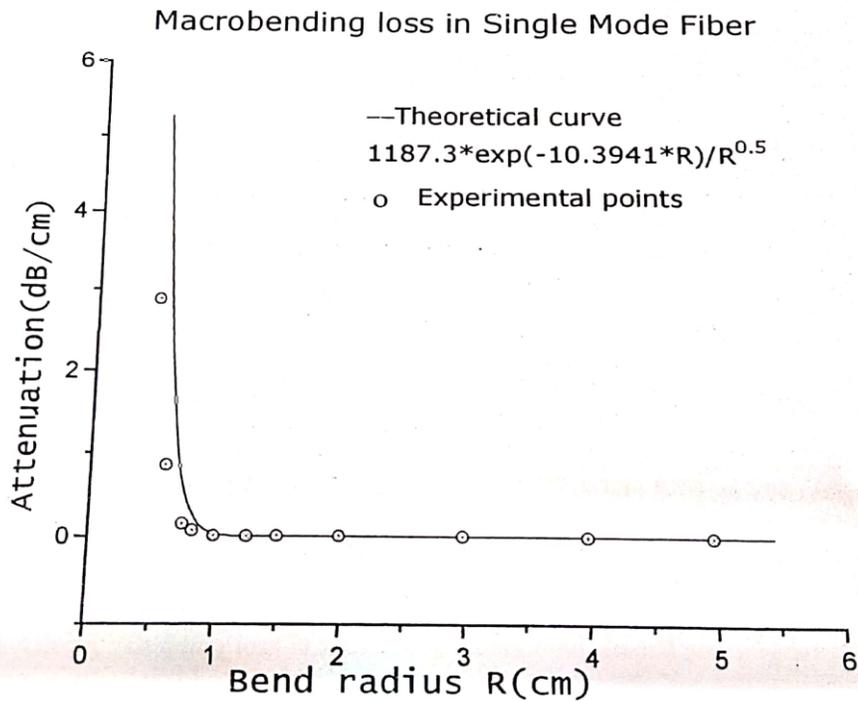


Fig. 7.4 Bend loss of a single mode step-index fiber as a function of bend radius. The fiber core diameter $\approx 4.2 \mu\text{m}$, $\Delta \approx 0.002$ and $v \approx 2.31$ at $0.633 \mu\text{m}$; points represents to the measured data and the continuous curve represents the theoretical curve, obtained using Eqs. (2) and (3).

Observations

Input power without any bend =

S.No.	Radius of the rod, R	No. of turns	Total length of the bent fiber, L	Output power	Power loss (dB)	Absorption coefficient (α)

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Result

A typical variation of experimentally observed bend loss per unit length for a single-mode fiber (Fibercore, SM600) is shown in Fig. 7.4. The single-mode step-index fiber used for the experiment was having a nominal core diameter $\approx 4.2 \mu\text{m}$, $\Delta \approx 0.002$, $V \approx 2.31$ at the He-Ne laser wavelength ($0.633 \mu\text{m}$). In this figure, the filled circles show experimentally observed values, whereas the continuous curve shows the best fit to these experimental data. The experimental data usually starts deviating from the theoretical plot (obtained using Eq. 7.3), which may be because of not taking into account the transition loss. The procedure followed above for the bending loss measurement would not be suitable for multimode fibers since the bending loss per unit length in the fiber will be length dependent.