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Numerical Analysis of Bending and Microbending Losses in a Single Mode Step Index Optical Fiber

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Abstract
In this paper, we investigate bend loss in single mode step index optical fiber. We restrict our analysis to two bend losses involving macrobend and microbend. We use the software "Understanding Fiber Optics on PC". We find a minimum loss of zero dB for the operating wavelength of 1.3 µm, core radius of 4.0 μm, relative index difference of 0.35% and bending radius of 7 cm. This result may be an important consideration to design an optical fiber.
Keywords: *Optical fiber, bending losses, Micro bending losses, Transition losses, Spot-size*

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I. Introduction

An optical fiber is a transparent cylindrical filament of glass or polymer. It consists of a highly refractive index of core surrounded by a lower refractive index of cladding. Cladding is not necessary for light to propagate along with the core of the fiber. It serves several purposes [1]. It reduces scattering loss that results from dielectric discontinuities at the core surface and adds mechanical strength and protects the core from surface contaminants. Light propagates longitudinally into the core following the total internal reflection law. Optical fiber is the superior medium for transmitting signals from one end to the other end. A general communication system of an optical fiber comprises of an optical transmitter, transmission medium and a receiver [2]. The transmitter consists of a light source and it is modulated by a suitable drive circuit. The receiver consists of a detector, followed by an electronic amplifier and a signal recovery unit. Thus, the basic optical fiber system would consist of a source and a photodetector at the two ends of the fiber link. The most important advantages of optical fiber as compared to electrical wire are transmission loss, very high bandwidth (BW), smaller size and much lighter weight [3]. After long research, optical fiber experiences a very little power loss. In 1970, the first optical fiber was produced with attenuation at 20 dB/km but now the attenuation has reached at 0.18 dB/km [4]. Nowadays optical fiber forms the basis for local, national and international telecommunication networks. But surprisingly it is true that almost all the power loss has not been removed totally. Especially, some bending losses is, of course, unavoidable e.g., shipping and storage, optical manufacturing and installations.

Extrinsic matter increases the signal attenuation of the fiber. It is caused by two external mechanisms: macro bending and microlending [5]. Macro bending occurs when a fiber is bent in a tight radius. Then the bend curvature creates an angle that is too sharp for the light to be reflected into the core and some of it escapes through the fiber cladding, causing signal attenuation.

Further, when a fiber is jacketed and cabled, it is subjected to varying pressures at different places due to the surface roughness of the materials used for jacketing or cabling. These cause small and irregular transverse displacements of the fiber of varying degrees. These are referred to as microbeads in the fiber [6]. We perform a numerical analysis of Bending and Micro bending Losses in a single-mode step-index optical fiber (SMSIF). We use SMSIF because it is the best road of communication for minimum dispersion [7]. This type of fiber has distinct advantages over multimode step index optical fiber (MMSIF) because of low intermodal dispersion i.e., broadening of transmitted light pulses. The present study has been done using the software "Understanding Fiber Optics on a PC". We use the software throughout the study and prepare the data tables and graphical representations. The minimum loss is obtained at 1300 *nm* of operating wavelength, 4.0 *µm* of core radius and 0.35% of relative index differences.

II. Materials and Methods

We use the software GST of "Understanding Fiber Optics on a PC" for this work [6]. The software is designed to give the reader a numerical appreciation and also graphical representations of the characteristics of the fiber. It allows the user to interactively change the parameters to create the examples and also provides a platform to perform a simple calculation based mainly on a step-index fiber. Light propagation into the fiber depends on various parameters especially the refractive index of core-clad, the wavelength of light (λ), ***V***- number and core radius (a). Borosilicate glass is generally used as the core material of the glass fiber because of its low thermal expansion, non-flammability, transparency etc. In the present work, borosilicate glass has been chosen as the core material, whose refractive index is 1.470.

Fiber optics is full of jargon but it's important to understand it. One of the more confusing terms to many is the wavelength. For fiber optics with glass fibers, light in the infrared region is used which has a wavelength longer than visible light, typically around 850, 1300 and 1550 *nm*. Single-mode fibers usually operate in the 1300 *nm* or 1550 *nm* regions, where the attenuation is least [8]. The wavelength of 1300 *nm* has been chosen for the present study because the lower the wavelength, the less expensive the optics [9]. For 1300 *nm* the typical values of relative index difference between core and cladding are within the region (0.25-0.35%).

One of the more important characteristics of the fiber is normalized frequency. It is also called ***V***- number. For SMF, ***V***- values must be less than 2.405. In order to keep the spot size as small as possible, the ***V***-values are around 2.015-2.388. The other important characteristic of the fiber is the radius of core. For SMF, it is in the range of 1-5 μm. The radius of the core of 4 μm has been chosen for the present study because below this value ***V***-number decrease and above this more light is scattered.

However, the entire light waves do not propagate through the fiber. Only certain numbers propagate through it. These light wave directions are called ***V***- number and are written as

$$V = \frac{2\pi}{\lambda} a\sqrt{(n_1^2 - n_2^2)}$$

where a is the core radius, λ is the operating wavelength, n_1, n_2 are the refractive index of core and cladding. Refractive indices of core-clad are one of the most important parameters of the optical fiber. The propagation of light mostly depends on this parameter. During bending purposes or manufacturing processes, a small change in

$$\Delta = \frac{n_1 - n_2}{n_1}$$

refractive index can cause fiber attenuation. So, to reduce bend loss, we should emphasize the refractive indices of the fiber. The fractional difference Δ between the refractive indices of the core and cladding is known as the fractional refractive index change. It is expressed as

This parameter is always positive because n_1 must be greater than n_2 [5]. For increasing the refractive index of cladding with the constant refractive index of core, refractive index differences decreases and hence ***V***- number also decreases.

Acceptance angle (i_m) is the maximum angle that a ray can have relative to the axis of the fiber and propagate down the fiber. The higher value of $\boldsymbol{i_m}$ allows most of the light to propagate along with the fiber. For SMF, the larger the acceptance angle, the more the fiber will be bent. It is written as

$$i_m = \frac{1}{\sin\sqrt{(n_1^2 - n_2^2)}}$$

A bend in the fiber can be a straight fiber section jointed with a bent fiber cross-section. The bent fiber is also jointed with the straight fiber. The power from the straight fiber is coupled to the field in the bent fiber. The field in the bent fiber propagates through to be coupled into the following straight section. Thus, there are transition losses at the joints and there is loss in the curved fiber section generally termed as pure bend loss.

In a bent fiber, the field launched from the mode of the straight fiber does not propagate as a mode and the field distribution changes substantially. One important change is that the field no longer has a maximum at the fiber axis and it shifts slightly in the direction away from the center of curvature of the fiber bend. This shift is rather difficult to obtain exactly, but using the approximation of the fields, a simple expression has been obtained [10]

$$d_c = \frac{\beta^2 W_G^4}{2R_c}$$

where β is the propagation constant of the mode in the straight waveguide, R_c is the radius of the curvature of the bend and W_G is the Gaussian spot size. Thus, at the transition, there is effectively a transverse offset in the fields. The pure bend loss coefficient in a step-index fiber is given by

$$\gamma_c = (\frac{\pi}{32})^{1/2}(\frac{U}{VK_1W})^2(\frac{W_\infty^3}{a^4R_c})^{1/2}\exp[-\frac{4\lambda^2}{3\pi^2W_\infty^3n_1^2}R_c]$$

It should be noted that in evaluating the above expression all the quantities, a, W_G, R_c must have the same unit R_c. The units of γ_c would then be inverse of that length and the loss of a length of the fiber could be obtained by multiplying the length by γ_c. The loss per unit would be given by [5]

$$\alpha_c = 4.343\gamma_c$$

The modal field gives all the relevant characteristics of the SMSIF. It has a functional form and can be entirely described by its Gaussian spot-size. However, the modal field, have more feature than a Gaussian function can describe and hence several characteristics of a fiber can be described in terms of spot- sizes which represent the transverse extent of the fiber. There are four spot-sizes in literature.

The first spot-size known as the Petermann-1 spot size is related to the loss due to angular misalignment at a joint between two fibers. It is written as [11]

$$W_0^2 = \frac{2\int_o^\infty \varphi^2(r)r^2dr}{\int_0^\infty \varphi^2(r)rdr}$$

The second spot size $(\overline{W})$, known as the Petermann -2 spot sizes is related to loss due to transverse offset at a splice between two fibers. It is written as

$$\overline{W} = a\sqrt{2}\,\frac{J_1(U)}{WJ_0(U)}$$

Third spot size (W_∞), known as the Petermann -3 spot size is related to bending losses of the fiber which is written as

$$W_\infty^2 = \frac{\lambda}{\pi n_1(\beta - k_0 n_2)} \approx (\frac{2a}{W})^2$$

The fourth spot size is the Gaussian spot size (W_G).

III. Results and Discussion

When a fiber is bent at a large angle, strain is placed on the fiber along the region. Then the bending strain affects the refractive index of the core-clad and the critical angle of the light in that specific area. As a result, light traveling in the core can refract out and macro bend loss occurs.

The present study is to find out the suitable parameters of the optical fiber with minimum bending losses. The following fig.1 shows how macrobend loss changes with the change of refractive index differences between core and cladding. Here the values of *λ*, n_1, *a* are fixed and we only change the refractive index of cladding. For different values of cladding, we get different value of refractive index differences between core and cladding. And then we observe total bend loss in terms of refractive index differences for 3.75 cm of bending radius.

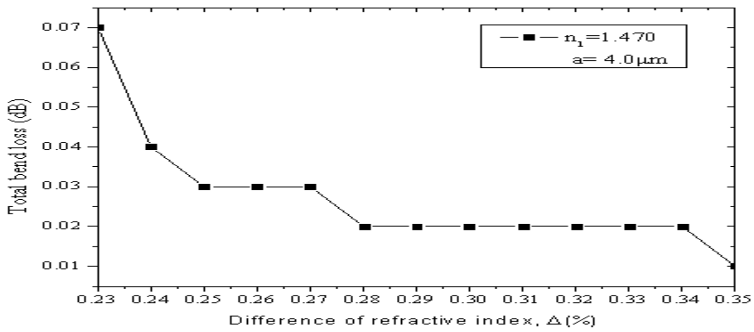

Figure 1: Total bend loss as a function of refractive index difference.

We see that bend loss decreases with increasing refractive index differences. In this figure it is observed that when $\Delta(\%)$ = 0.35, bend loss is only about 0.01dB. When $\Delta(\%)$ = 0.23, bend loss is 0.07 dB. Therefore, it is observed that larger core-clad index difference decreases the bend loss and smaller core-clad index difference increases the bend loss of the fiber. In the following Tab.1, we perform the total macro bend loss due to pure bend loss and transition loss as a function of bending radius. Here total macrobend loss in terms of bending radius has been observed for three set of parameters where we only change the refractive index differences between core and cladding. We fixed the operating wavelength of 1300 nm, 4.0 µm of core radius and 1.470 of the refractive index of core.

Table 1: Total macro bend loss as a function of bending radius (R_c).

$\Delta(\%)$	Total bend section (cm)	$R_c\,(cm)$	Total bend loss(dB)
0.35	100	8	0.00
		9	0.00
		10	0.00
0.30	100	8	0.00
		9	0.00
		10	0.00
0.25	100	8	0.01
		9	0.01
		10	0.00

From the Tab.1, we see that total macrobend loss decreases with increasing bending radius. Alternatively, if the bending radius decreases to an inch or less, optical power loss increases rapidly. The graphical representation between total macrobend loss and the bending radius is shown in the following fig.2.

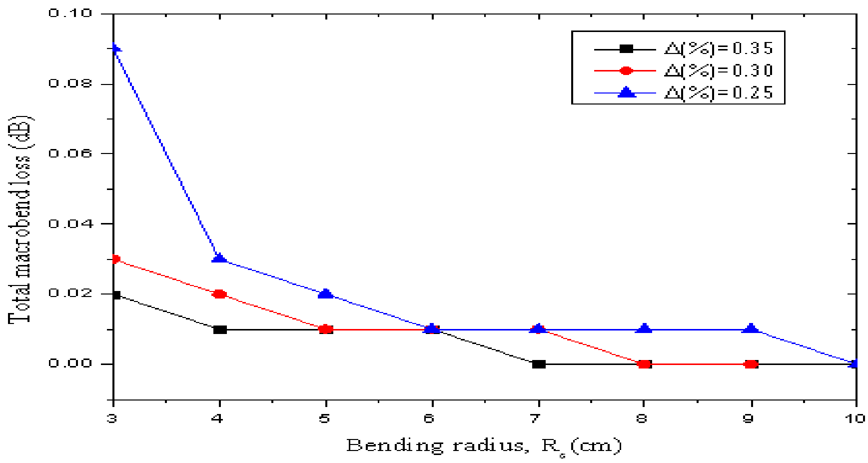

Figure 2: Total macro bend loss as a function of bending radius (R_c).

From the Fig.2, it is observed that when Δ (%) = 0.35 total macro bend loss becomes zero at 7 cm of bending radius and above of R_c. Therefore, the fiber of first set of parameters will be bent more than 7 cm with zero bend loss. For $\Delta(\%) = 0.30$, total macrobend loss becomes zero at 8 cm and above of R_c . Again for $\Delta(\%) = 0.25$, total bend loss becomes zero at 10 cm and above of R_c. Thus, for the first combination, the fiber can be bent more than the others two combinations.

Unlike a macrobends, microbands don't have any regular shapes or distributions along the fiber. These may have different bend radii over small sections and are distributed randomly over the length of the fiber. It is rather difficult to model losses in such cases and only estimates have been made [12]. Microbending introduces slight surface imperfections which can cause mode coupling between adjacent modes. The upper limit on the microbending loss in each fiber is decided by the spot size W_∞ and the lower limit by $\overline{W}$. Hence in the design process our goal is to achieve the value of $W_\infty/\overline{W}$ as close to unity as possible. The set of parameters whose ratio of these spot-sizes is very close to unity will be able to reduce microbend losses. The ratio of spot-sizes for the three set of parameters has been shown in the following Tab.2.

Table 2: Ratio of two spot - sizes ($W_\infty / \overline{W}$) for three set of parameters

$\Delta(\%)$	$W_\infty(\mu m)$	$\overline{W}(\mu m)$	$W_\infty / \overline{W}$
0.35	4.648	4.360	1.06
0.30	5.265	4.610	1.14
0.25	6.152	4.951	1.24

As discussed in theory, second spot - size ($\overline{W}$) is related to transverse offset and third spot-size (W_∞) is related to bending losses. Table 2 shows that for the first set of parameters the values of the spot sizes become smaller than the others and also the ratio of $W_\infty / \overline{W}$ are very close to unity. For that case micro bend losses will reduce to zero. Now the summery of our study for the above three set of parameters is shown in Tab. 3.

Table 3: Total macro bend and micro bend loss for three set of parameters

$\Delta(\%)$	i_m (deg.)	V	R_c cm	loss (dB)	$W_\infty / \overline{W}$
0.35	7.10	2.388	7	0.0	1.06
0.30	6.60	2.222	8	0.0	1.14
0.25	5.98	2.105	10	0.0	1.24

Table 3 shows the results of both macro bending and micro bending losses of the optical fiber for three set of parameters. It is mentioned that larger the acceptance angle, more the fiber can be bent. Also at larger acceptance angle, most of the light will propagate along the fiber and for that case minimum power loss is occurred. From this Tab.3 we see that for first set of parameters, acceptance angle is larger than others. Therefore, the fiber of this combination will be bent more ($\geq$ 7 cm) than the others combination without any information loss. Also, at larger ***V***- number, the modal fields are well confined and the spot-sizes are not shifted highly and hence it gives lower values of spot-sizes. We see that for the first sets at 0.35% of refractive index difference, the ***V***- values are larger than the others combination and its spot-sizes ratio become very close to unity. That is for the first case, the fiber is capable to curve more than others without any loss of information. The present study suggests that the fiber of the first combination is better combination to make a fiber with low macro bending and micro bending losses.

IV. Conclusion

In the present study the bending and micro bending losses in the single mode step index optical fiber have been studied by changing the fiber parameters. From this analysis, it has been found that the fiber is very sensitive with its parameter change. For small changes of refractive index, the bending and micro bending losses are changed drastically. A minimum bending and micro bending losses are obtained at 1300 *nm* of the operating wavelength, 4.0 μm of the core radius, and 0.35% of the refractive index difference and 7 cm of the bending radius. This parameter can be used to design an optical fiber and for the fabrication process.

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