Study of Bending Losses in Optical Fibers using COMSOL

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Abstract: In FTTH, optical fibers are frequently bent at the corners of the walls causing the propagating light in the fiber to radiate away which results in transmission losses and limits reach of the fiber network. A large number of studies have been reported in the literature to compute bend-induced losses in fibers. However, most studies assume simple refractive index profiles such as step-index profile and include the effects of stress due to bending of fiber in an *ad hoc* manner by modifying the bend radius R to effective bend radius $R_{eff} = (1+\delta)R$, where δ is a number in the range {0.28, 0.31}. For simulations with arbitrary refractive index profiles, which are encountered commonly in practice, the refractive index of the bent fiber is modified into refractive index of an equivalent straight fiber using simple conformal mapping techniques. In this paper, we present a completely different approach for computing the modified refractive index profile of the bent fiber and compute bending losses. Specifically, we apply the geometrically exact beam theory (GEBT) and stress-optics law to account for stress effect of bent fibers, followed by conformal mapping to account for geometric effect of bending in order to obtain the modified refractive index profile. The modified index is imported to COMSOL using Interpolation function, which performs linear interpolation of the data. A 2D cross section of the fiber, with core and cladding is defined as the geometry of the model. We use Electromagnetic Waves, Frequency Domain physics, and Mode Analysis study from Wave Optics module for solving the wave equation to obtain the effective index of the propagating modes in the bent fiber. A Perfectly Matched Layer (PML) is included in the geometry to avoid the unwanted interference of mode fields confined in core and reflecting the radiation from cladding interface. We study the effect of PML thickness on effective index and find that the sensitivity is negligible for PML thickness of 7λ. A Physics-Controlled mesh with Fine Element size was applied to the geometry. Bend Loss was computed from the imaginary part of the effective index for bend diameters in the range {6, 20} mm at 1550 nm. Finally, by comparing our results with those of the literature, we find that our formulas agree well with experiments, especially at low bend diameters.

Introduction

Optical fibers installed for FTTH applications are bent at the corners of walls, causing severe power loss and affecting the transmission efficiency. Several studies both theoretical and experimental have been carried out to investigate in-plane bend losses in single and multi-mode optical fibers [1, 2]. Conventionally, in the theoretical analysis for macro-bending, the fiber geometry was limited to core followed by infinitely extending cladding [1, 3]. But in practical scenarios fiber has finite cladding and is covered by another layer, known as buffer coating. In [4] Renner considered the third layer in the geometry and formulated macro-bend loss in optical fibers, with some approximations. In all the derived formulas the value of bending radius R was replaced with effective bend radius $R_{\text{eff}} = 1.28 - 1.31R$ as an elasto-optic correction factor in conformal mapping, to account for stresses acting on the fiber. This kind of approximation may give valid results but with a compromise on accuracy.

In this paper, we propose a new approach for estimating bend losses in optical fibers. In section 2, we describe the possible sources of modification of refractive index, and techniques applied to obtain the modified index. We apply geometrically exact beam theory (GEBT) and conformal mapping to obtain the modified refractive index of the bent fiber. In section 3, we explain the procedure followed and various inputs provided in COMSOL simulations to estimate the induced bend loss. In section 4, we study the influence of perfectly matched layer (PML) thickness and mesh element size on simulation results, and optimize them to minimize any variations in simulation results. In section 5, we extend our simulations to bend insensitive fiber and compare the results with experiments.

Simulation Strategies

When a fiber is bent, the path length of the light is not same along the cross-section of the fiber. In the bent fiber shown in Fig. 1(a) light reaches faster to point A (lower refractive index) when compared to that of point B (higher refractive index). The equivalent refractive index profile is obtained by following conformal mapping [2]. Here the curved waveguide is mapped to an equivalent straight waveguide shown in Fig. 1(b), with coordinate transformation, whose refractive index is given by $n_G = n\, exp(x/R)$. Where n the refractive index of is bent fiber, and n_G is the index of equivalent straight fiber. For higher bends, i.e., $x << R$ the refractive index is multiplied by the factor $\left(1 + \frac{x}{R}\right)$.

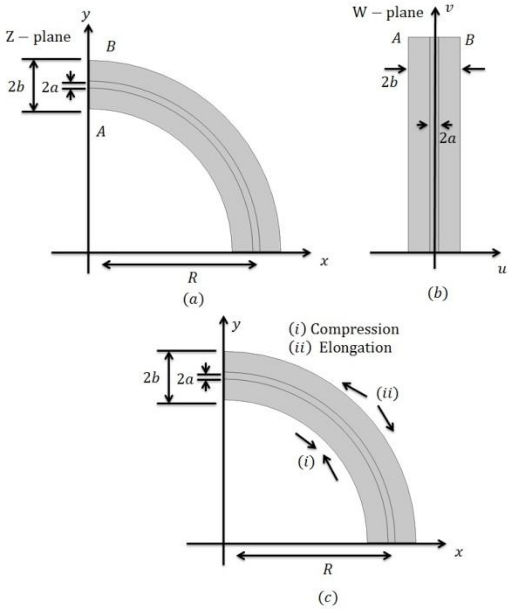

Fig. 1: (a) Schematic of the bent fiber, (b) Mapping of curved waveguide to equivalent straight guide by conformal mapping, (c) Stresses experienced by fiber under bending condition

In addition to the geometric effect, a bent fiber experiences stress as shown in Fig. 1(c). The inner side of the fiber experiences compression, increasing the refractive index. And the index decreases at the outer end due to the fiber elongation. This index variation is opposite to the change due to geometric effect, and the stress effect counters the geometric effect, and hence loss value decreases.

Geometrically exact beam theory (GEBT) was applied to estimate modified refractive index for each bending diameter. GEBT captures the bending and computes the corresponding strain tensor. This strain tensor when employed into stress-optic law, given by (1), gives the modified refractive index of the bent fiber due to stress effect $n_S(x, y)$.

$$n_S(x,y) = n(x,y)\left[1 - \frac{n^2}{2}\left(P_{11}\epsilon_1 + P_{12}(\epsilon_2 + \epsilon_3)\right)\right] \quad (1)$$

Where $P_{11} = 0.113$ and $P_{12} = 0.252$ are the stress optic coefficients, $\epsilon_1, \epsilon_2, \epsilon_3$ are the principle strains obtained from GEBT and $n(x, y)$ is the index profile of unbent fiber. Once $n_S(x, y)$ is obtained the profile is multiplied with the factor $\left(1 + \frac{x}{R}\right)$ to account for geometric effect. For simulations, we modeled the refractive index of the standard G652 optical fiber fabricated using modified chemical vapor disposition (MCVD) system, which usually shows a dip in the core [5]. Fig. 2 shows the modeled refractive index profile of straight fiber along with the modified index obtained after including both the effects and also the modified index profile by using the elasto-optic correction factor in conformal mapping. The significant deviation in the modified indices obtained in both cases indicates the error in estimated bend loss using later.

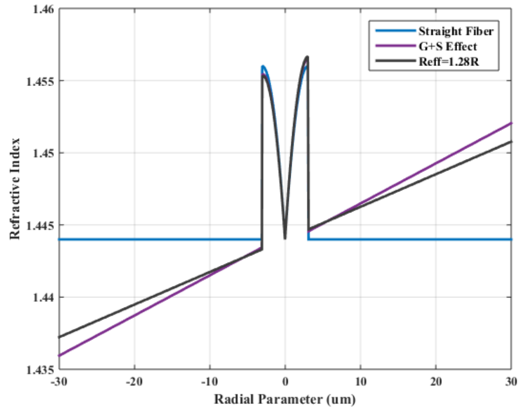

Fig. 2: Refractive index profile of the fiber, modelled with a central dip, for straight fiber and fiber bent at 10 mm diameter using GEBT and elasto-optic correction factor.

COMSOL Simulations

In COMSOL, a 2D cross-section of two concentric circles, as shown in Fig. 3(a), is generated as geometry of the model. The modified refractive index due to both stress and the geometric effect is imported to COMSOL using interpolation function, where it performs linear interpolation of the data. We solve the wave equation given by (2) using electromagnetic wave, frequency domain (ewfd) physics in wave optics module.

$$\nabla \times \nabla \times \vec{E} - k_0^2 \epsilon_r \vec{E} = 0 \quad (2)$$

where, $\vec{E}$ is the electric field distribution of mode, k_0 is the free space wave number and ϵ_r is the relative permittivity of the region of interest.

A perfectly matched layer (PML) is added as a third layer to the geometry to avoid the reflections from cladding interface to interfere with the mode confined in the core. We applied boundary condition of the perfect electric conductor, with zero initial conditions, to the exterior boundary.

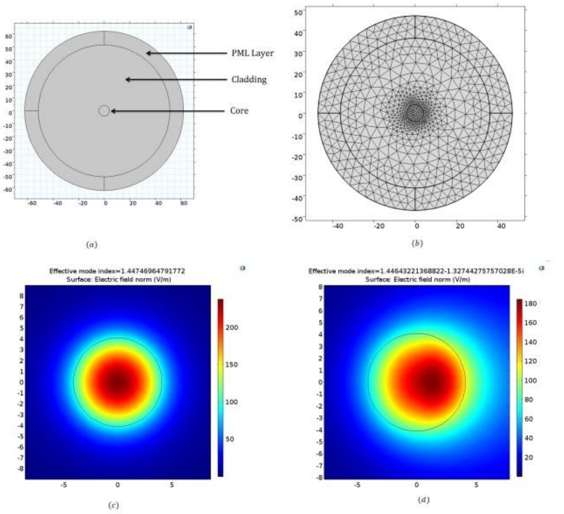

Fig. 3: (a) Cross-section of the optical fiber used in calculation of bend loss from COMSOL simulations. The core and cladding radius are 3.05 and 62.5μm respectively. The PML thickness was taken to be 7λ, (b) Physics controlled mesh with fine element size applied to the geometry, (c) LP01 mode propagating through the fiber when it is not bent, (d) LP01 mode when the fiber is bent at a diameter of 10 mm.

A physics-controlled mesh, with fine element size, as shown in Fig. 3(b), was applied to the geometry. We compute the modes and the effective mode index for straight and bent fibers, using mode analysis study. Here we ask COMSOL to search for modes propagating through the fiber, with their effective index close to core refractive index, at the operating frequency $f = c/\lambda$. Fig. 3(c), (d) shows the modes along with their effective index value obtained in case of straight and bent fiber. When the fiber is bent, effective index turns complex, and its imaginary part is used to estimate the bend loss following the expression:

$$2\alpha\left[\frac{\text{dB}}{\text{turn}}\right] = \frac{20}{\ln(10)}\frac{2\pi}{\lambda}\,\text{Im}\{n_{\text{eff}}\} \times \pi d \quad (3)$$

where d is the bend diameter, λ is the operating wavelength (1550 nm), and $\text{Im}\{n_{\text{eff}}\}$ indicates the imaginary part of the effective index. Bend Loss obtained for bend diameters ranging from $6 - 20$ mm is given by blue curve in Fig. 4.

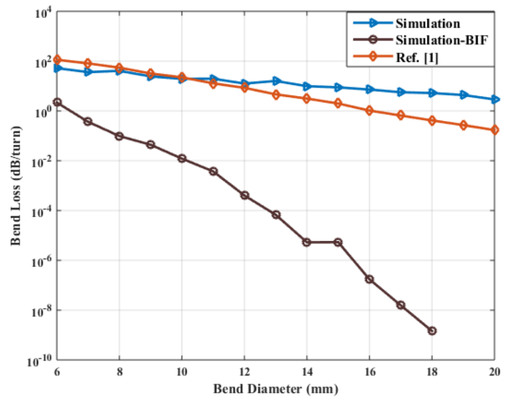

Fig. 4: Results of loss due to in-plane bending of the fiber in COMSOL simulations for both normal and bend insensitive fiber for bend diameters ranging from $6 - 20$ mm. Also shown are loss calculated using formula given in reference [1].

We compare the simulation results with the formula derived in [1], which underpredicts the loss for larger bend diameters and overpredicts for lower bend diameters.

PML Thickness and Meshing Optimisation

As mentioned in Section 2, PML thickness was applied around the fiber geometry to absorb the unwanted reflections from cladding interface. The effective mode index of the bent fiber is highly sensitive to the thickness of PML applied. Hence a proper study of the impact of PML thickness on the effective index of the mode propagating in the standard G652.D fiber is done. We varied the thickness from $1\lambda - 7\lambda$ and the effective index in each case in noted. And the variation of imaginary part of the effective index for bend diameters of $9.5,\ 11.5$ and 15.5 mm are shown in Fig. 5. The index variation is higher for lower bend radii. The thickness is optimized to 7λ, beyond which the variation in the effective index, and proportionally in bend loss is negligible.

COMSOL solves this mode propagation problem using full-vectorial finite element method (FEM) mode solver. Hence the element size used in meshing the geometry has significant amount of influence on the results, as shown in Fig. 5(b). As the bend loss is varying for coarse meshing, we applied a fine mesh as the loss variation is minimal in this region.

Bend Insensitive fiber

After the loss for standard G652 fiber is computed, we next applied our GEBT theory to the bend-insensitive fiber (BIF), designed with a trench in the index profile as shown in Fig. 6. The trench design of the fiber index helps in reducing the induced loss in fiber when bent [5], making the fiber bend-insensitive. The specifications of the trench such as trench index difference, width, and location from the core are obtained by following standard ITU-T recommendations for G652 fibers, explained in a more detail manner in [5]. The bend loss induced in a bend-insensitive fiber for a bend diameter of 10 mm was demonstrated experimentally in [5].

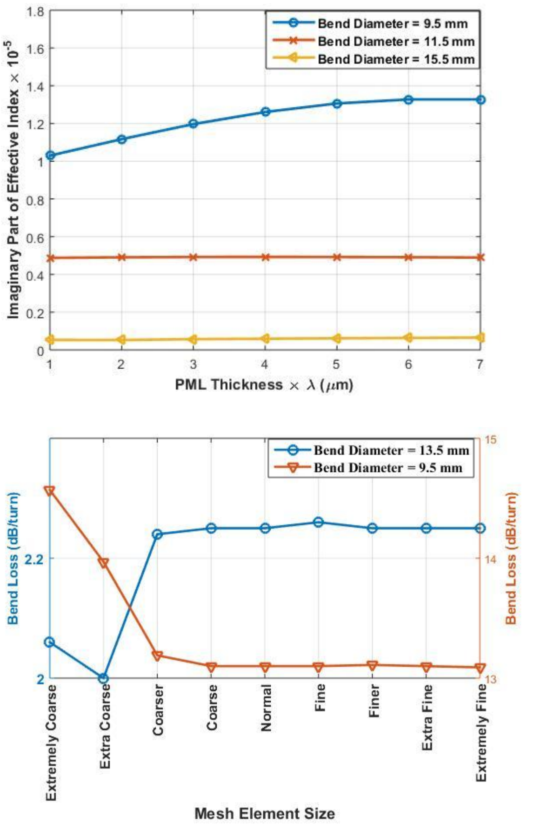

Fig. 5: Sensitivity of simulation results with (a) PML thickness and (b) Mesh element size

Now we apply our procedure of GEBT and conformal mapping to the trench index of bend-insensitive fiber to obtain the modified refractive index shown in Fig. 6. And then perform simulations in COMSOL to estimate the induced bend loss shown in Fig. 4, which is very low in comparison with the standard fiber. These results support the use of trenched index fiber, as bend-insensitive fibers, to increase the stability of fibers towards bending.

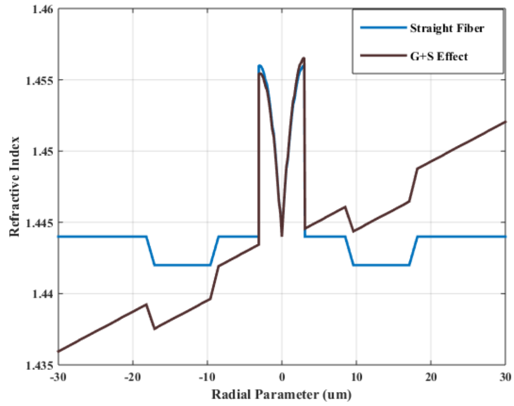

Fig. 6: Refractive Index of bend insensitive fiber (BIF) with a trench in cladding, (a) in unbent case and (b) fiber bent at 10 mm bend diameter.

In [5], the experimental measurements of bend loss induced in BIF for the diameter of 10 mm over the wavelength range of $1400 - 1650$ nm was reported. We have compared our simulation results with these experimental results at 1550 nm. These experiments were repeated several times and then averaged out giving the peak loss of 0.014 dB/turn with a standard deviation of ± 0.0023 dB/turn and mean-loss of 0.012 dB/turn at 1550 nm wavelength. Comparing these experimental results with our simulation, we estimate a bend loss of 0.0119 dB/turn for the 10 mm bend diameter. As the predicted value is close to the experimental measurements, we can term our simulation method to be valid and accurate to estimate bend losses.

Conclusion

In this paper, we have proposed an accurate method to study the behavior of in-plane bend loss induced in a standard and bend-insensitive optical fiber. We performed electromagnetic simulations in COMSOL and validated it with experiments. In simulations, we applied geometrically exact beam theory (GEBT) and conformal mapping technique to compute the modified refractive index of the fiber bent in a loop. We imported the modified index into COMSOL and solved the wave equation, for the effective index of the modes propagating in bent fiber and calculated bending loss. We optimized the simulation parameters PML thickness and mesh element size to minimize any variation in the results. We compared our simulation results for BIF with reported experimental measurements, which are in good agreement. Finally, we indicate that the proposed method in this paper is for single-mode optical fiber with specific refractive index profile, but we can extend the same to multi-mode fibers and the fibers of different refractive index profiles.

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