Numerical Study of Bending Losses in Optical Fibers with Arbitrary Profile Index

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Abstract. In this work, the bending loss was numerically studied within the COMSOL environment, where the general formula for profile index including graded and step-index types was adopted. The study showed an increase in bending loss with decreases bending radius, decreases core radius and increases wavelength. The graded order is effective up to \( g = 1.75 \) after which the loss is constant. There is an oscillating change in loss caused by interference between the outgoing and reflected waves from the boundaries, which becomes clearer as the loss itself increases.

Keywords: bent losses, graded-order, fundamental mode

1. Introduction

Optical fiber plays a role in high-quality and high-speed telecommunications development [1]. The loss of optical energy will occur when a fiber undergoes a macro-bend of the limit curvature radius, i.e. a dielectric waveguides lose power by radiation if their axes are curved. It has negative effect of signal for communication system of optical fiber, on this basis, it was used as a useful feature to develop optical fiber for different purposes [2]. There are two mechanisms known to cause bend-induced loss, the first happens to the uniform bend owing to mismatch between the bent regions and direct modes. The other type happens within uniformly bent region where the refractive index profile of fiber is getting as skewed, to increasing linearly of refractive index on bend. Bending affects, the individual mode various according to distinct properties such as effective refractive index, intensity, phase distribution, etc. Bending an optical fiber is to introduce refractive lose [3] So, there are many efforts to reduce macro-bending losses for all types of optical fibers along the past few years, where fiber designs were proposed to meet several requirements for macro-bend losses [1, 4]. The limitation of the most serious to its validity is caused by dealing with undistorted field of the straight guide for its derivation, even if the loss of radiation is ignored, the field changes its form in the curved guide. Therefore, no existing formulae for modeling bend-losses of these fibers were presented, except for maximum or minimum prediction of the bend loss conditions in relation to parameters of fiber and wavelength. Bending loss of fibers are employed with many important purpose like a great importance for modern communications, especially with regard to techniques of multiplexing in the way to enhance the ability to send information, plays a central role with the design of fiber amplifiers and with a fiber laser to reduce...
higher-order to achieve single of effective regime of multi-mode fibers [5, 6, 7]. It has been shown in this work, that the effect of the four chosen parameters, spatially graded-order ($g$), wavelength of propagated wave ($\lambda$), core radius ($a$) and bending radius of a dielectric wave guide on the bending-losses ($L_b$) will be illustrated.

2. Methods

The wave front in the optical fiber must be perpendicular to the direction of propagation. The signal transmitted in core becomes faster than in cladding. As a result, loss in the signal transmitted energy through the optical fiber will appear where the speed of light must be increased as shown in Fig.1.

\[ L_b = 10 \log_{10} \left[ \exp(2\alpha L) \right] = 8.686 \alpha L \] (1)

Where $\alpha$ = macro-bending loss coefficient (function of optical fiber structure and material, bending radius, and wavelength of radiation used in the fiber). So, there are many approaches have been employed for evaluation it, a simple formula firstly proposed by Marcuse. The simplified formula for the bent optical fibers needs to be modified to include fiber stress by utilizing the effective bend radius. Therefore, the modified index distribution must be presented by transforming the circularity curved fiber to equivalent straight fiber. This leads to, the tilted index distribution with respect to original. An increasing away from the center of the bend (curvature of the bent fiber can be a tilted refractive index), as shown in Fig.2.
Fig.2. profile index, a) with bent and b) without bent

The well-known formula of modified refractive index distribution with slow bent ($R \gg x$) as the first approximation read as:

$$n_{equ}(x, y) = n_{mat}(x, y) \exp(x/R) \approx n_{mat}(x, y)(1 + x/R)$$

(2)

Where $x$ is the displacement from the core center in curvature axis, $R$ radius of bent and $n_{mat}$ is the refractive index-profile to unbend fiber. Because of compression along fiber's inner half, towards the bend center and tension along the outer half of fiber, $n_{mat}$ becomes vary according to the relation [9].

$$n_{mat}(x, y) = n(x, y) \left[1 - \frac{n^2(x, y) x}{2R} \left[P_{12} - \nu(P_{11} + P_{12})\right]\right]$$

(3)

where $P_{11}$ and $P_{12}$ = components of photo-elastic tensor, $\nu$ = ratio of Poisson and $n(x, y)$ = the refractive index-profile of the unbend (straight) fiber and so called profile-grading, defined as [10], [11].

$$n(x, y) = n_{core}\sqrt{1 - 2\Delta(\rho/a)^g}$$

(4)

where $\rho = \sqrt{x^2 + y^2}$, the parameter $\Delta = (n_{core} - n_{clad})/n_{core}$, $n_{core}$ and $n_{clad}$ = refractive index in center of the core and the cladding, respectively, and $g$ = graded-order, it plays an important role when waves propagated the optical fiber and gives a strange properties depending on the profile indices of the different graded orders that shown in Figure 3. Accordingly, graded-order will be an important issue to construct the bent losses.
Fig. 3. Refractive index profiles for different graded-orders [10]

Where $2\alpha$ is the coefficient of power loss, $\kappa = \sqrt{k_{\text{core}}^2 - \beta_z^2}$ and $\gamma = \sqrt{\beta_z^2 - k_{\text{clad}}^2}$ = field decay rates of core and cladding, respectively, $k$ and $\beta$ are the propagation constants for free space and the guided mode in the unbent waveguide, respectively, $V = \sqrt{\kappa^2 + \gamma^2} = \text{the normalized frequency}$, $K_{m\pm 1} = \text{Bessel function of 2nd kind}$. 

3. Results and Discussion

COMSOL environment was used to determine the relationship between wavelength and effective refractive index. COMSOL works on a finite element method (FEM) basis which is built on the basis of dividing the cross section into small parts and forming the mesh. A perfectly matched layer (PML) is added with thickness $\epsilon$ 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. Concerning profile index, the same formula as in Eq.(4) with the replacements (by $\alpha$ and by $\epsilon$) were applied. The type and accuracy of the mesh are chosen in order to achieve better accuracy with a suitable operating time for the computer. A study of this subject requires controlling of four factors: the core radius, the bending radius, the wavelength and the graded order. Fig. 4 represents a selected sample for the fundamental mode in step index fiber by changing part of these factors. It is evident that the amount of energy that will be outside the core is subject to these factors.
Fig. 4. Fundamental mode at $g = \infty$ for (a) $R_b = 2 \text{mm}$ and (b) $\lambda = 1.55 \mu \text{m}$

Fig. 5 represents the relationship of the bending losses with the graded, where core radius is at $a = 10 \mu \text{m}$. Generally, the loss decreases with the graded order until reach the limits of $g \geq 1.75$, then the loss is constant. That is, the type of profile index affects only the loss at the smaller graded orders. When the graded order decreases, the distribution width of the profile index will be small. Therefore, the Gaussian distribution of the fundamental mode may have a greater width, and therefore we expect the mode portion outside the core to be large with a decrease in the graded order. On the other hand, the loss is greatly reduced as the bending radius increases and vice versa. The reason for this decrease is due to the fact that a greater portion of the propagated pulse will be outside the core with a decrease in the bending radius.

Fig. 5. Bending losses and graded order

Fig. 6 presents bending losses of the step index fiber as function of core radius for different values of $R_b$ at $\lambda = 1.55 \mu \text{m}$. 3dB is the maximal variation when a radius is $2 \text{mm}$. At a small bending radius, the
random variations appear very clear due to the increased interface section between the cladding and the PML layers. As the bending radius increases, loss and corresponding random variations will be decreased. In addition, at a small core, the loss is significant and vice versa. This is due to the inability of the core to confine the propagated pulses (small core).

Fig. 6. Bending losses Vs. core radius

Fig. 7 illustrates bending losses of step index fiber as function of core radius for different wavelengths at \( R_b = 2 \text{mm} \). It is evident that the greater wavelength causes more losses, and the losses generally decrease with an increase in the core radius. Random variation is very clear in the case of large losses, and the interpretation of that is the same as what was mentioned in Fig. 6. The greater loss at large wavelengths is due to the difficulty of confinement of the propagated pulses, especially for the small core radius.

Fig. 8 explains the bending losses of the step index fiber as function of \( \lambda \) for core radius at \( R_b = 2 \text{mm} \). A smaller radius causes the largest bending losses, and the losses, generally, increase with wavelength due to a decrease in the confinement opportunity for the greater wavelengths. At small core radius, the random variations are also appeared very clear. This behavior may change when the selected bending radius is changed during the simulation, where the largest losses effects appear with a smaller bending radius.
Fig. 7. Bending losses Vs. core radius

Fig. 8. Bending losses Vs. wavelength

Fig. 9 explains the bending losses as a function of $R_b$ for different values of graded orders at $\lambda = 1.55 \mu m$, $a = 10 \mu m$. Notice that, the most significant effects appear at $g = 0.5$ and decrease with increasing graded order. Generally, the effects are closely related to each other, with graded orders values in the limit $g \geq 1$. Generally, after $R_b = 4 mm$, the bending losses are very small for all graded orders and this is due to a decrease in the mode portion that will be outside the core with an increase in the bending radius.
4. Conclusions

In conclusion, a part of the fundamental mode may be outside the core, its amount depends on the simulation coefficients, which can be chosen to minimize the bending loss. It would appear that decreasing the bending radius and core increase loss, while loss increases with the wavelength. The loss decreases with the graded order, then it is fixed after $g = 2.5$. There is an oscillating change in the loss, which increases with decreasing of bending radius or core radius and the increase of wavelength.

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