Empirical Study of Helical Bend Loss in Optical Fibers

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Keywords: Helical Bend Loss, In-plane Bend Loss, Empirical Formula, Analytical Loss Formula.

Abstract: We propose a method to estimate helical bend loss in optical fibers and extend the method to predict the loss in a different fiber. In our approach, we consider the in-plane bend loss as the reference and approximate the loss curve as an exponential function decaying with bend diameter. For in-plane bends, we compute loss over the bend diameter range of $9.5 - 19.5$ mm at 1550 nm wavelength. For helical bends, we perform experiments for the same range of bend diameters and pitch values of $2, 4, 5, 7$ and 10 mm. We extend the exponential function approximation to the experimental measurements of helically wound fibers and obtain an empirical formula to estimate the helical bend loss. We find that for a given bend diameter, the bend loss increases initially with the pitch, attains a maximum value and then decreases below the corresponding in-plane bend loss. We extend the empirical formula developed for a single fiber with a specific refractive index to evaluate the helical bend loss in another fiber. We conduct the in-plane bend loss experiments for the new fiber and repeat the exponential fit and obtain fit coefficients. We calculate the fit coefficients for different pitch values using empirical formula and predict the helical bend loss. We compare the predicted loss with corresponding experimental measurements, which are in good agreement.

1 INTRODUCTION

Bending in optical fibers causes the transmitting light to radiate away from the core, resulting in the power loss. It is a widespread problem in FTTH applications, where the fibers are bent at the tight corners of the wall. In addition to this, the effect of bending on the field properties such as polarisation and its intensity is utilized to advantage in few applications. The circular birefringence exhibited by a helically curved fiber is widely used in fiber optic sensors (Soh et al., 2003). Fibers with helically twisted cores are designed to achieve single-mode operation of large mode area fiber lasers (Huang et al., 2016). Evaluation of helical bend loss in fiber is a topic of interest for these applications.

The analysis of the fields and computation of the power loss in helically wound fibers, specified by bend diameter d and pitch p, involves complex coordinate transformations and tedious numerical calculations. In (Marcuse, 1976b), the author suggest the replacement of bend radius R in the in-plane bend loss formula (Marcuse, 1976a), by $R/\sin^2\theta$ where θ is the helix angle given by $\tan^1(2\pi R/p)$ to obtain helical bend loss. In section 2, we show that the formula predicts the higher loss for all pitch values and bend diameters.

In (Frikha et al., 2013), authors performed a mechanical modelling of the translational invariant helical structures and theoretically calculated the strain tensors corresponding to the axial load applied on single wire and seven wire strand bent in the form of helix. In (Treyssède et al., 2013), authors have extended the analysis of (Frikha et al., 2013) to theoretically study the wave propagation in a helical waveguides. A full vectorial modelling of helical core fibers with the helicoidal coordinates were transformed to cartesian coordinates was performed in (Napiorkowski and Urbanczyk, 2014). A similar transformation was used in (Wilson et al., 2009), where authors chose numerical path using finite difference time domain (FDTD) method to solve for the fields in the bent fiber and studied the propagation characteristics of modes in a helically curved fiber. A principal disadvantage of these methods is that they are responsive for simple step index profiles and become more complicated for general refractive index profiles. Further, the numerical methods have convergence issues, especially for large pitch and diameters.

In this paper, we suggest an empirical formula to evaluate helical bend loss in optical fibers, with arbitrary refractive index profiles. In section 2, we de-

Velamuri, A., Sharma, I., Gupta, S. and Krishnamurthy, P.
Empirical Study of Helical Bend Loss in Optical Fibers.
DOI: 10.5220/0007407402290234
In *Proceedings of the 7th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2019)*, pages 229-234
ISBN: 978-989-758-364-3

scribe the experimental set-up used to measure the in-plane and helical bend loss. We approximate the bend loss curve with the diameter as an exponentially declining curve. In section 3, we derive an approximate analytical formula to compute helical bend loss and compare the results with the experiments. In section 4 we analyze the experimental measurements of helical bend loss, extend the concept of the exponential fit to the loss curves of different pitch values and obtain an empirical formula. In section 5, we extend the empirical method to predict the helical bend loss of a different fiber. We compare the empirical results with experiments and validate our approach to be applicable to different fiber types with arbitrary refractive index profiles.

2 EXPERIMENTAL SETUP

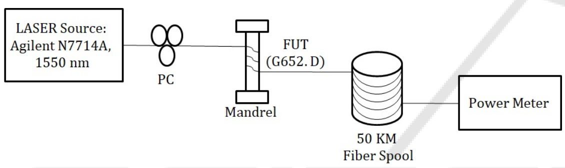

Figure 1: Schematic of the experimental set up used to measure the bend loss induced in helically wound fibers. PC- Polarisation Controller, FUT- Fiber Under Test.

Fig. 1(a), shows the schematic of the experimental set-up used to measure the loss induced in the in-plane bend, specified by bend diameter d and helically wound optical fibers, defined by bend diameter d and pitch p. The light from the laser source, Agilent N7714A, tuned at 1550 nm wavelength is coupled into the fiber under test (FUT). In experiments, we used single-mode G652.D fiber spool of 50 Km length to measure the bend loss induced. In the first step, we noted the output power reading after FUT using power meter without applying any external forces on the fiber. In the second step, we bent the fiber on mandrels and recorded the output reading. We subtracted the results of the two steps and obtained the loss induced due to bending alone. First, we performed the experiments for the in-plane bending of fiber for a diameter range of $9.5-19.5$ mm. We measured the bend loss for single turn at each bend diameter thrice and averaged the results.

In Fig. 2 we plotted the in-plane bend loss measured. The loss obtained through experiments for in-plane bend is fit to an exponential function of bend diameter d:

$$2\alpha[\text{dB/turn}] = ae^{-b(d-d_0)}. \tag{1}$$

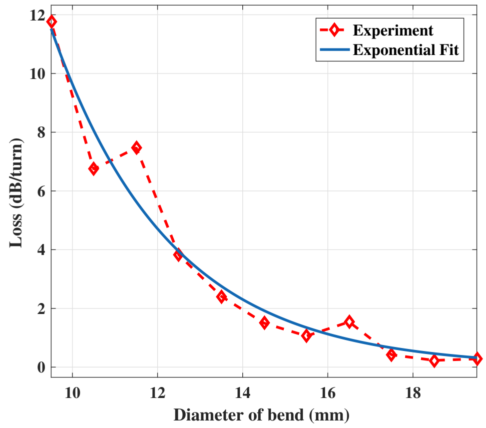

Figure 2: Results of loss due to in-plane bending of the fiber. Also shown is exponential fit of the experimentally measured losses.

In (1), a and b are the fitting coefficients found by least-squares fit to the experimental data and $d_0 = 9.5$ is the offset. For the data in Fig. 2, we found a and b to be 11.52 and 0.3577 respectively. As expected, the in-plane bend loss decreases exponentially with increasing bend diameter (Marcuse, 1976a).

After the completion of bend loss measurement for in-plane bend, we followed the same procedure and measured the loss induced in helically wound optical fibers. For helical bends, we considered the same range of diameters as the in-plane case for the pitch values $2,4,5,7$ and 10 mm. For each bend diameter and pitch, we bent the fiber for 1 and 3 turns and averaged the bend loss per turn of both the results. Similar to the in-plane bend experiments, helical bend loss reported here is an average of three readings. In Fig. 3 we plotted the helical bend loss recorded in the experiments, for the pitch values of 2 and 7 mm, along with the loss computed using the formula given by Marcuse in (Marcuse, 1976b). From the plots, we can unequivocally state that the expression in (Marcuse, 1976b) overestimates the loss at all bend diameters and for all pitch values.

3 ANALYTICAL FORMULA

A general formula to compute loss in a bent fiber is given by (Schermer and Cole, 2007)

$$2\alpha = \frac{\int_{-\infty}^{\infty} \left| \frac{F(U_{x=0})}{H_\nu^{(2)}(\gamma R)} \right|^2 d\beta_y}{\pi^2 k_{clad} R} \tag{2}$$

where $F(U_{x=0})$ is the Fourier transform of normalized mode field distribution of the bent fiber at $x = 0$, $H_\nu^{(2)}$

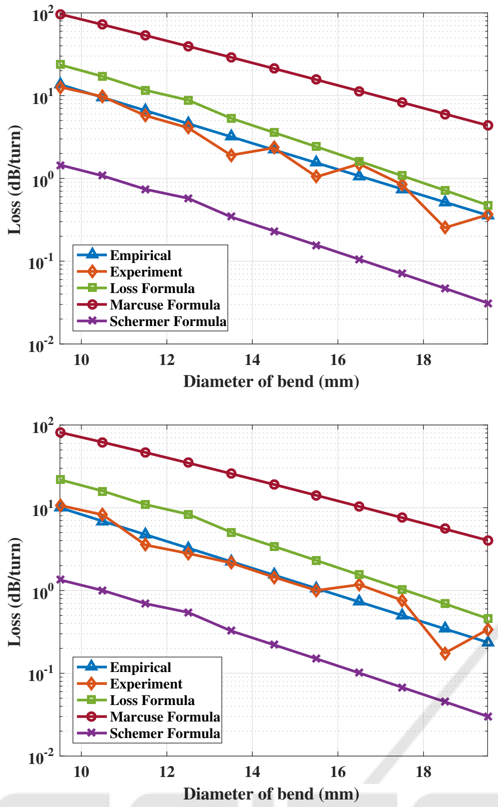

Figure 3: Comparison of helical bend loss results, for pitch value of (a) 2 mm, (b) 7 mm.

is the Hankel function of order ν and second kind, R is the bend radius and γ is the field decay rate in cladding. Comparing the modes propagating in a bent waveguide with a straight waveguide we obtain a relation (Marcuse, 1972):

$$\nu\phi = \beta_z z, \tag{3}$$

where β_z is the propagation constant in a bent fiber, ϕ is the azimuthal angle, ν is the angular propagation constant and z is the arc length along the central axis of bent waveguide. Here, we take z as the arc length along the helix axis, denoted as SA in Fig. 4, instead of the axis along planar bend as considered in (Marcuse, 1972), which is given by

$$z = \frac{R\phi}{\sin\theta}, \tag{4}$$

where θ helix angle given by:

$$\theta = \tan^{-1}\left(\frac{2\pi R}{p}\right). \tag{5}$$

From (4) the angular propagation constant in a helically bent fiber is given by

$$\nu = \frac{\beta_z R}{\sin\theta}, \tag{6}$$

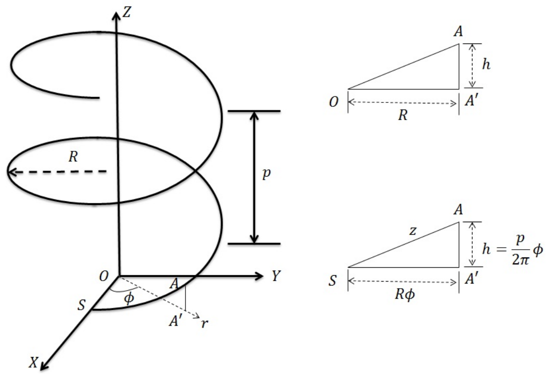

Figure 4: Schematic of the fiber bent in the form of helix.

In (Marcuse, 1976a), Marcuse has expressed the radiation field outside the core of a bent fiber as the superposition of cylindrical waves and approximated them with Hankel functions. He expanded the Hankel function arguments at the origin, i.e., at $x = 0$, and employed the propagation constant and γ at the same point to calculate the radiation outside the core. In our work, we make the same approximation but derive a modified expression of Hankel function for helically bent fibers with the use of (6). In this derivation, we use the following approximation for Hankel function (Marcuse, 1972)

$$H_\nu^{(2)} = +i\frac{e^{\nu(\alpha-\tanh\alpha)}}{\sqrt{\frac{\pi}{2}\nu\tanh\alpha}}, \tag{7}$$

where,

$$\cosh\alpha = \frac{\nu}{n_2 k_0 R}. \tag{8}$$

For hyperbolic trigonometric functions, we have the relation

$$u = \tanh\alpha = \frac{\sqrt{\cosh^2\alpha - 1}}{\cosh\alpha}. \tag{9}$$

Substituting (8) in (9) we get

$$\nu\tanh\alpha \approx \frac{\gamma R}{\sin\theta}. \tag{10}$$

To evaluate the argument of the exponential function in (7), we use the relation

$$\alpha = \tanh^{-1} u = u + \frac{1}{3}u^3 + \frac{1}{5}u^5 + \ldots\ldots., \tag{11}$$

where u is given by (9). Using (9), we can rewrite (11) as

$$\alpha - \tanh\alpha = \frac{1}{3}u^3 + \frac{1}{5}u^5 + \ldots\ldots. \tag{12}$$

Substitution of the modified expression for angular propagation constant (6) and (9) in to (12) gives

$$\alpha - \tanh\alpha = \tanh^{-1}\left(\frac{\gamma}{\beta_z}\sin\theta\right) - \frac{\gamma}{\beta_z}\sin\theta$$

$$+\frac{1}{2}\cos^2\theta\left(\frac{\gamma}{\beta_z}\sin\theta\right)\frac{\beta_z^2}{\beta_z^2-\gamma^2\sin^2\theta}$$
$$-\left(\frac{n_{clad}k_0\sin\theta}{\beta_z}\right)^2\left(\frac{\gamma}{\beta_z}\sin\theta\right)\frac{x}{R}\frac{\beta_z^2}{\beta_z^2-\gamma^2\sin^2\theta} \tag{13}$$

We expand (13) and neglect the higher order terms to obtain the expresssion

$$\nu(\alpha-\tanh\alpha)=\frac{\gamma^3R}{\beta_z^2\sin\theta}+\frac{1}{2}\frac{\gamma^2\cos^2\theta}{\beta_z^2-\gamma^2\sin^2\theta} \tag{14}$$

Substituting (10), (14) into (7), we obtain the modified expression of Hankel function for helically bent fibers, which is given by

$$H_\nu^{(2)}(\gamma R)=+i\sqrt{\frac{2\sin\theta}{\pi\gamma R}}$$
$$\exp\left(\frac{\gamma^3R}{\beta_z^2\sin\theta}+\frac{1}{2}\frac{\gamma^2\cos^2\theta}{\beta_z^2-\gamma^2\sin^2\theta}\right). \tag{15}$$

The analytical loss formula obtained with the modified Hankel function expression (15) is given by

$$2\alpha=\frac{\sin^{1/2}\theta\pi^{1/2}\kappa^2\exp\left(-\frac{2\gamma^3R_{\text{stress}}}{\beta_z^2\sin\theta}-\frac{\gamma^2\cos^2\theta}{\beta_z^2-\gamma^2\sin^2\theta}\right)}{2R_{\text{stress}}^{1/2}\gamma^{3/2}V^2K_{m-1}(\gamma r_{core})K_{m+1}(\gamma r_{core})}, \tag{16}$$

where V is the V-number of the fiber, K_m is the modified Bessel function of order m, κ is the field decay rate in the core region, m is the azimuthal mode number ($m=0$ for LP_{01} mode, r), $R_{\text{stress}}\approx 1.28R$ is the elasto-optic factor to account for the stresses experienced by the bent fiber.

In Fig. 3 we compared the loss computed from the analytical formula with the experimentally measured loss. We observed that the analytical formula (16) predicts the loss closer to the experiments, compared to the expression given by Marcuse in (Marcuse, 1976b). But the formula still overpredicts the loss by a finite proportion. We can speculate the error in Hankel function approximation and the mode field deformations as the reasons for the differences still present. In Fig. 3 we also plotted the loss computed with the bend loss formula given in (Schermer and Cole, 2007). In (Schermer and Cole, 2007), authors expanded the Hankel function arguments at core-cladding boundary, i.e., at $x=a$, instead of origin and derived a corrected loss formula. The recommended formula in (Schermer and Cole, 2007) tends to underestimate the loss.

4 EMPIRICAL FORMULA

In experiments, we observed the helical bend loss behave non-monotonically with the pitch. The loss initially increases with the pitch, reaches a maximum value and then starts to decrease. Neither the analytical loss formula (16) nor the expression given in (Marcuse, 1976b) show the non-monotonic behaviour of helical bend loss with the pitch. In this section, based on the experimental results, we develop an empirical formula to compute loss in helically wound fibers for given pitch and diameter.

We extended the exponential fit approach, explained in 2, to the experimentally measured helical bend loss, where we now treat a and b as functions of helix pitch p. For each p, we obtain a and b by fitting experimental loss data as described in the previous section. Fig. 5 shows the result of this procedure where we plotted a and b as a function of pitch. We note that a initially increases and then decreases to p, and b initially decreases and then increases to p. We obtained an empirical relation between a, b with p by fitting the data in Fig. 5 by a function of the form given by

$$a(p)=\begin{cases} m_1p+a(0), & 0\le p\le p_{peak} \\ m_2(p-p_{peak})+a(p_{peak}), & p>p_{peak}\end{cases} \tag{17a}$$

where, m_1 is the increasing slope, m_2 is the decreasing slope, p_{peak} is the value of pitch where the slope changes from m_1 to m_2.

$$b(p)=\begin{cases} m_3p+b(0), & 0\le p\le p_{min} \\ m_4(p-p_{min})+b(p_{min}), & p>p_{min}\end{cases} \tag{17b}$$

where, m_3 is the decreasing slope, m_4 is the increasing slope, p_{min} is the value of pitch where the slope changes from m_3 to m_4. We showed the values of these empirical fit parameters in Table 1.
The result of the fits are shown as solid lines in Fig. 5. With a and b obtained from (17), we calculate the helical bend loss according to

$$2\alpha(p,d)=a(p)\exp\left(-b(p)(d-d_0)\right). \tag{18}$$

In Fig. 3, we compared the loss computed using the empirical formula with the experimental measurements, for pitch values of 2 and 7 mm. We observed that the empirical loss, predicted using (18), agrees well with the experiments when compared to the loss calculated by the analytical formula (16).

Table 1: Values of empirical parameters used in (17).

m_1[dB/mm]	$a(0)$[dB]	m_2[dB/mm]	p_{peak}[mm]
1.07	11.52	−0.73	2
m_3 [/mm^2]	$b(0)$[/mm]	m_4 [/mm^2]	p_{min}[mm]
−0.0016	0.37	0.0077	5

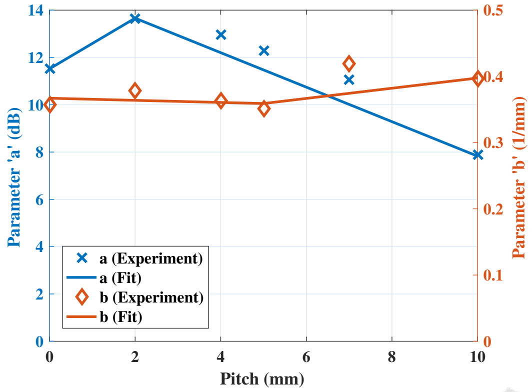

Figure 5: Variation of fitting parameters a and b with pitch p. The solid line is the fitting function given in (17).

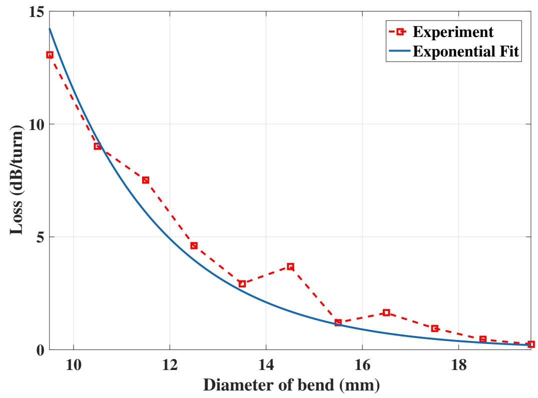

Figure 6: Results of loss due to in-plane bending of the new fiber sample along with its exponential fit.

5 VALIDATION OF EMPIRICAL APPROACH

The empirical formula developed here is for single mode fiber considered in this paper, we can easily extend our approach to other fiber types. The idea of the empirical formula is to reduce the computational complexity involved in the helical bend analysis and provide a simple method to predict the helical bend loss induced in an optical fiber from either the numerically calculated or experimentally measured in-plane bend loss. The in-plane bend loss of optical fibers has been studied very extensively in literature with several closed-form analytical formulae developed (Peng et al., 2017), (Zheng et al., 2016) and a few numerical methods using BPM simulations proposed (Schermer and Cole, 2007). To summarize the discussion, we can use the empirical parameters given in Table. 1 to compute helical bend loss in any fiber if we know either the experimentally measured or numerically calculated in-plane bend loss.

In this section, we extended our empirical approach to the different type of fiber to validate our method being independent of the type of fiber used. Here, in the second phase of our experiments, we again used a single-mode G652.D fiber, but from a different manufacturer with different refractive index profile. We first performed in-plane bend loss measurements on the new fiber sample and plotted the results in Fig. 6. Next, we followed the exponential fit procedure, explained in section 2, on the new results and obtained the fit parameters a and b as 14.28 and 0.42 respectively.

Further, we used the newly obtained values for $a(0)$ and $b(0)$, the empirical parameters given in Table. 1 and calculated the a and b parameters at different pitch values. We substituted these values in (18) and computed the helical bend loss for different pitch values. To authenticate the obtained loss values, we performed helical bend loss experiments on the new fiber sample at 2 and 7 mm pitch and compared the results in Fig. 7. The close agreement of the empirical and experimental results validates our empirical approach to compute helical bend loss of any fiber with arbitrary refractive index profiles.

6 CONCLUSIONS

In this paper, we have proposed an empirical approach to predict the helical bend loss in fibers, and extended the approach to compute bend loss in a different fiber. We considered the experimentally measured in-plane bend loss as the reference and approximated the loss curve with bend diameter as an exponentially decreasing curve $ae^{-b(d-d_0)}$. We extended the exponential fit approach to the experimentally measured helical bend loss, with a and b now considered as the functions of the pitch and obtained the empirical formula. We observed that the helical bend loss does not straight away decrease with the pitch. Instead, it initially in-

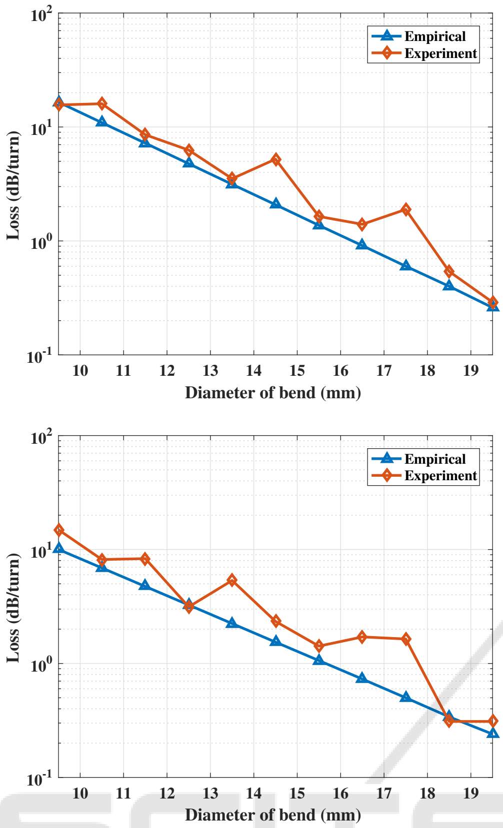

Figure 7: Comparison of empirical and experimental results of new fiber sample for pitch values of (a) 2 mm and (b) 7 mm.

creases with pitch reaches a maximum value and then starts to decline below the corresponding in-plane bend loss. We developed the formula for a single-mode fiber with a specific refractive index and then extended the method to evaluate the bend loss in a different fiber. We used the obtained empirical parameters of one fiber and predicted the helical bend loss in other based on its measured in-plane bend loss. The empirically computed loss in both the fiber samples is in close agreement with the experiments. We have also calculated helical bend loss with an analytical loss formula, which predicts loss closer to the experiments when compared with the expression given by Marcuse in (Marcuse, 1976b). Finally, we point out that the empirical approach proposed in this paper eliminates the complex coordinate transformations involved in helical bend analyses and gives an uncomplicated approach to estimate loss closer to the experiments based on the in-plane bend loss data.

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