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Polarization Dependence of Bend Loss for a Standard Singlemode Fiber

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Abstract: Polarization dependence of bend loss caused by the polymer coating layer for a standard singlemode fiber (SMF28) is investigated theoretically and experimentally. Bend loss for SMF28 for both the TE and TM mode is calculated separately. Normalized polarization dependent loss is proposed for the characterization of the polarization sensitivity of bend loss for different bend radii. Corresponding experimental tests are presented, which agree with the theoretical results. Both the theoretical and experimental results show that the polymer coating layer has a significant influence on the polarization dependence of bend loss.

OCIS codes: (060.2310) Fiber optics; (060.2430) Fibers, single-mode.

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1. Introduction

It is well known that a radiation loss occurs when a singlemode fiber is bent. The bend loss has been regarded as an adverse effect in the context of optical transmission. However, bend fibers can also be optimized as novel optical components which can be employed in optical communications or optical sensing [1-3]. Bend loss for a standard singlemode fiber (SMF28) has been investigated theoretically and experimentally in our previous research and it has been indicated that the polymer coating layer, which offers the mechanical protection, has a significant influence on the bend loss when the bending radius is relatively small, e.g., within the range from 8 to 13 mm for the wavelength ranged from 1500 to 1600 nm [4]. In Ref. [3] the macrobending SMF28 has been developed to act as an edge filter through optimizing the bending length and bending radius according to the required discrimination in bend loss over

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the wavelength range. Utilizing this novel low cost edge filter, an all-fiber ratiometric wavelength measurement system has been demonstrated.

For an edge filter employed in wavelength measurements, low polarization dependence is also desired besides the discrimination in bend loss over the wavelength range. However, the investigation on bend loss for SMF28 in Ref.[4] and the corresponding optimal design in Ref. [3] are based on the scalar approximation, i.e., the polarization dependence of bend loss has not been considered yet. For weakly guiding singlemode optical fibers, scalar approximation of the wave equation works well for the analysis of the light propagation. Generally speaking, the difference in the refractive index between the polymer coating layer and the cladding layer is much higher as compared to that between the cladding and core. The reflectance of the radiated field occurring at the interface between the coating layer and cladding layer is believed to differ for different polarization states, which can lead to polarization dependence of the bend loss due to the coupling between the reflected radiated field and the quasi-guided fundamental mode. However, to the best of our knowledge, the previously published investigations on the bend loss for the singlemode fiber were carried out for a scalar approximation [4-7].

This paper presents both theoretical and experimental investigation on the polarization sensitivity of macrobending fiber with a relatively small bending radius. In Section 2, the calculation formulation of bend loss of the singlemode fiber is refined for the TE and TM mode separately, which takes account of the respective boundary condition at the interface between the cladding and the coating layer. The normalized polarization dependent loss (PDL) is proposed for better characterization of the polarization dependence for different bend radii. Section 3 presents the corresponding experimental tests, which show a good agreement with the theoretical results. Both the theoretical and experimental results show that the coating layer has a significant influence on the polarization sensitivity of bend loss.

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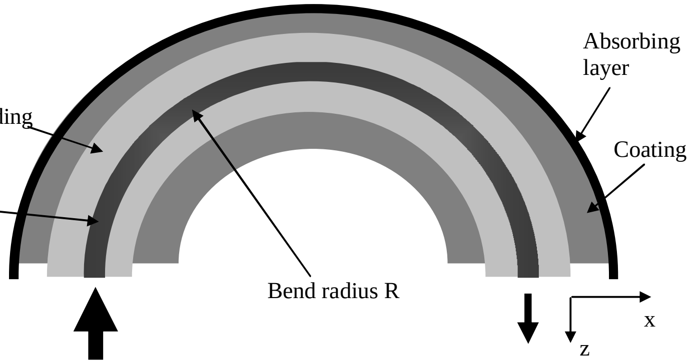
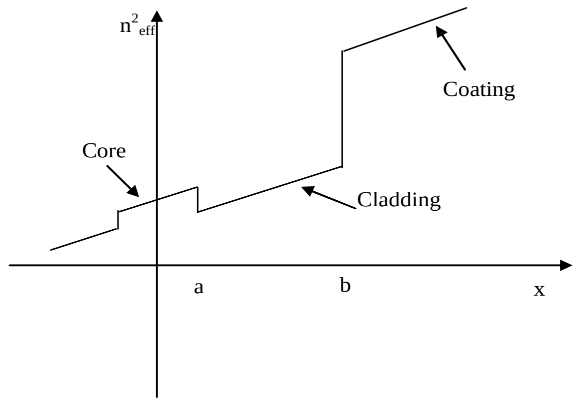
2. Calculation of bend loss for TE and TM mode



(a)



(b)

Fig.1. (a). Schematic structure of a bending fiber consisting of core, cladding, coating and absorbing layer; b) squared effective index profile with conformal mapping of the bending fiber.

Figure 1(a) presents a schematic structure of a bending fiber consisting of a core, cladding, coating and absorbing layer. The function of the absorbing layer is to absorb the radiated field that penetrates through the coating layer as presented in Ref. [3] so that the influence of the interface between the coating layer and air on the bend loss is removed. The structure is equivalent to a core-cladding-infinite coating structure. For this structure, the reflection of the radiated field occurring at the interface between the cladding and coating has a significant effect on the bend loss when the bend radius is relatively small due to the whispering-gallery mode caused by the interface.

Conventionally to predict the bend loss, the formulas developed in Refs. [5-7] can be employed. However, the formulas presented in these references are based on the scalar approximation. Calculation of bend loss taking account of the polarization of the propagation light can be based on a rigorous three-dimensional full-vector wave equation using a cylindrical coordinate and be solved with alternative numerical methods, such as the beam propagation method (BPM) or finite-difference (FD) method [8, 9]. These numerical methods can be used to calculate the bend loss for the TE and TM modes separately [TE mode: the polarization direction is defined in the x-z plane; TM mode: the polarization direction is in the y-z direction; see Fig. 1(a)], but it is time consuming. According to the related investigations

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on the integrated bending waveguide, a conformal mapping can also be applied to the full-vector wave equation with a good approximation [10, 11]. In addition, for these normal bending waveguide structures (contrast to the bending waveguide based polarization rotators), the cross coupling of transverse field is neglectable. Therefore, a quasi-vector wave equation is a good approximation for the bending fiber. Based on the quasi-vector approximation, the transverse field distribution in the cladding and coating area of the bend fiber (exclude the interface between the cladding and coating) satisfies the equation [5, 6],

$$\nabla_t^2\psi(x,y)+\left[k^2n_{eff}^2(x,y)-\beta^2\right]\psi(x,y)=0 \tag{1}$$

Where ψ is the electric component E_y for the TM mode or the magnetic component H_y for the TE mode. $k = 2\pi/\lambda$ and λ is the wavelength in free-space. n_{eff} is the effective index distribution of the bending fiber and $n_{eff}^2(x,y)=n^2(x,y)(1+2x/R)$ as shown in Fig. 1(b). β is the complex propagation constant, of which the imaginary part is the bend loss coefficient α (the bend loss can be calculated by $L_s = 10\log_{10}(\exp(2\alpha L))$).

Reference [6] presented a detailed derivation for solving the bend loss coefficient based on some approximations, e.g., the curved interface between the cladding and coating is treated as a plane and the light field within the core is approximated by the unperturbed field of the straight fiber with infinite cladding. Following the approximations and formulations in that reference

$$\psi_q(x,y)=\frac{1}{2\pi}\int_{-\infty}^{+\infty}\left[D_q(\zeta)B_i(X_q)+H_q(\zeta)A_i(X_q)\right]\exp(-i\zeta y)d\zeta \tag{2}$$

where $X(x,\zeta)=\left(\frac{R}{2k^2n_q^2}\right)^{2/3}\left[\beta^2+\zeta^2-k^2n_q^2\left(1+\frac{2x}{R}\right)\right]$. B_i and A_i are Airy functions, respectively.

For the TM mode, with the boundary condition between the coating layer and cladding layer, we have

$$\begin{cases} D_1(\zeta)B_i[X_1(b,\zeta)]+H_1(\zeta)A_i[X_1(b,\zeta)]=D_2(\zeta)B_i[X_2(b,\zeta)]+H_2(\zeta)A_i[X_2(b,\zeta)] \\ D_1(\zeta)B_i'[X_1(b,\zeta)]+H_1(\zeta)A_i'[X_1(b,\zeta)]=D_2(\zeta)B_i'[X_2(b,\zeta)]+H_2(\zeta)A_i'[X_2(b,\zeta)] \end{cases}. \tag{3}$$

For the TE mode, the corresponding boundary condition between the coating layer and cladding layer is

$$\begin{cases} D_1(\zeta)B_i[X_1(b,\zeta)]+H_1(\zeta)A_i[X_1(b,\zeta)]=D_2(\zeta)B_i[X_2(b,\zeta)]+H_2(\zeta)A_i[X_2(b,\zeta)] \\ \frac{1}{n_1^2}\{D_1(\zeta)B_i'[X_1(b,\zeta)]+H_1(\zeta)A_i'[X_1(b,\zeta)]\}=\frac{1}{n_2^2}\{D_2(\zeta)B_i'[X_2(b,\zeta)]+H_2(\zeta)A_i'[X_2(b,\zeta)]\} \end{cases} \tag{4}$$

With these two different boundary conditions bend loss coefficient can be determined as α_{TE} and α_{TM} respectively, and consequently, we can calculate the bend loss for the TE and TM mode respectively, namely, Ls_{TE} and Ls_{TM} .

There is an anisotropic variation of the refractive index of fiber due to the mechanical stress caused by bending. To take account of the influence of the variation of the refractive index on fiber bend loss, a practical method in the calculation of the fiber bend loss is to introduce an elasto optical correction for the agreement with the experiment, i.e., using a so-

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called effective bending radius R_{eff} and $R_{eff} = (1.27 \sim 1.31) R_{\exp}$ ($R_{\exp}$ is the actual bending radius in the experiment). However, our previous investigation in Ref.[4] indicates that this elasto optical correction is not required for the SMF28 in the modeling for the considered bending radii, which suggests that the contribution of variation of refractive index for SMF28 to the bend loss is neglectable. Therefore, the stress effect on bend loss of the two polarization modes is neglected in this paper.

For SMF28, the refractive index of the core, cladding and coating layer is 1.4504, 1.4447 and 1.4782, respectively at the wavelength 1.55 μm, the radius of the core and cladding is a=4.15 μm and b=62.5 μm. For a bending radius from 8 to 13 mm and a bending length of 10 turns, the bend loss for TE and TM mode is calculated and presented in Fig. 2(a). From Fig. 2(a), it can be seen that because of the whispering-gallery mode, the bend loss does not increase monotonically. Using the conventional definition, the polarization dependent loss can be calculated by $PDL = Ls_{TE} - Ls_{TM}$ (dB) and for the bend loss presented in Fig. 2(a), the corresponding PDL are presented in Fig. 2(b). From this figure one can see that with the same bending length the polarization dependent loss of a bending fiber differs significantly from different bending radii. Similar to the bend loss, the absolute value of polarization dependent loss does not increase monotonically as the bending radius decreases, e.g., PDL for bending radius of 9 mm is much bigger than those of 8 and 8.5 mm.

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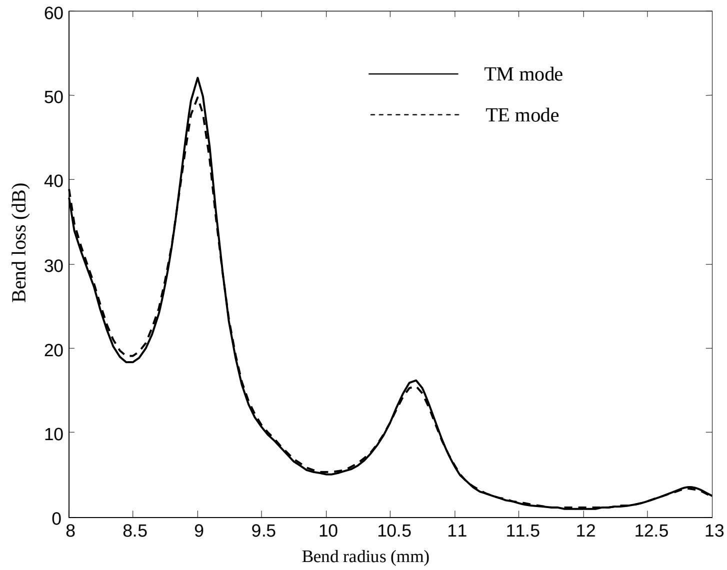
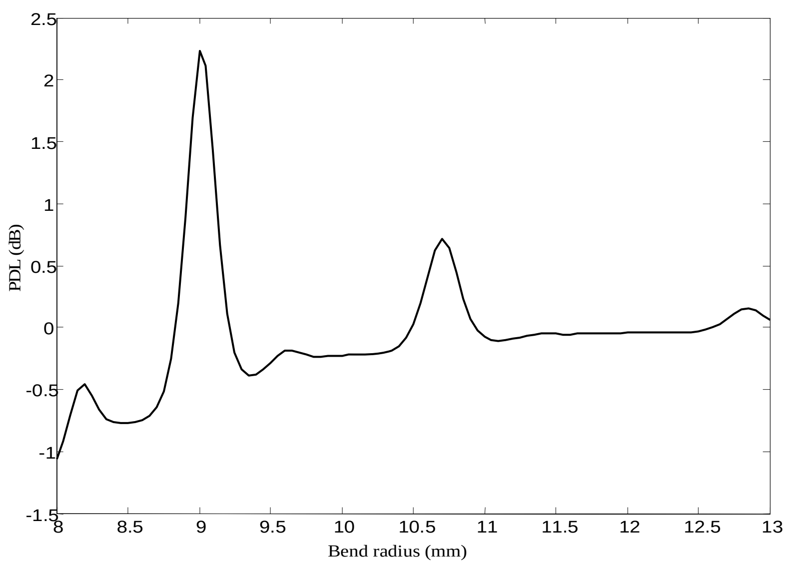


(a)



(b)

Fig. 2. (a). Bend loss for TE and TM mode; (b). Polarization dependent loss for the bending fiber.

For the design of bend loss edge filter comparison of polarization sensitivity for a bending fiber for different bending radii is required regardless of the bending length even where the actual loss values are closely matched. Choose the above SMF28 as an example and two cases are considered. Case 1) a bending length of 20 turns for bending radius of 10 mm and case 2) a bending length of 10 turns for the bending radius of 10.5 mm. Within the wavelength range from 1500 to 1600 nm, they have close bend losses as presented in Fig. 3(a), both of which are suitable to act as an edge filter for wavelength measurement if only considering the bend loss. However, the polarization dependent losses for these two cases

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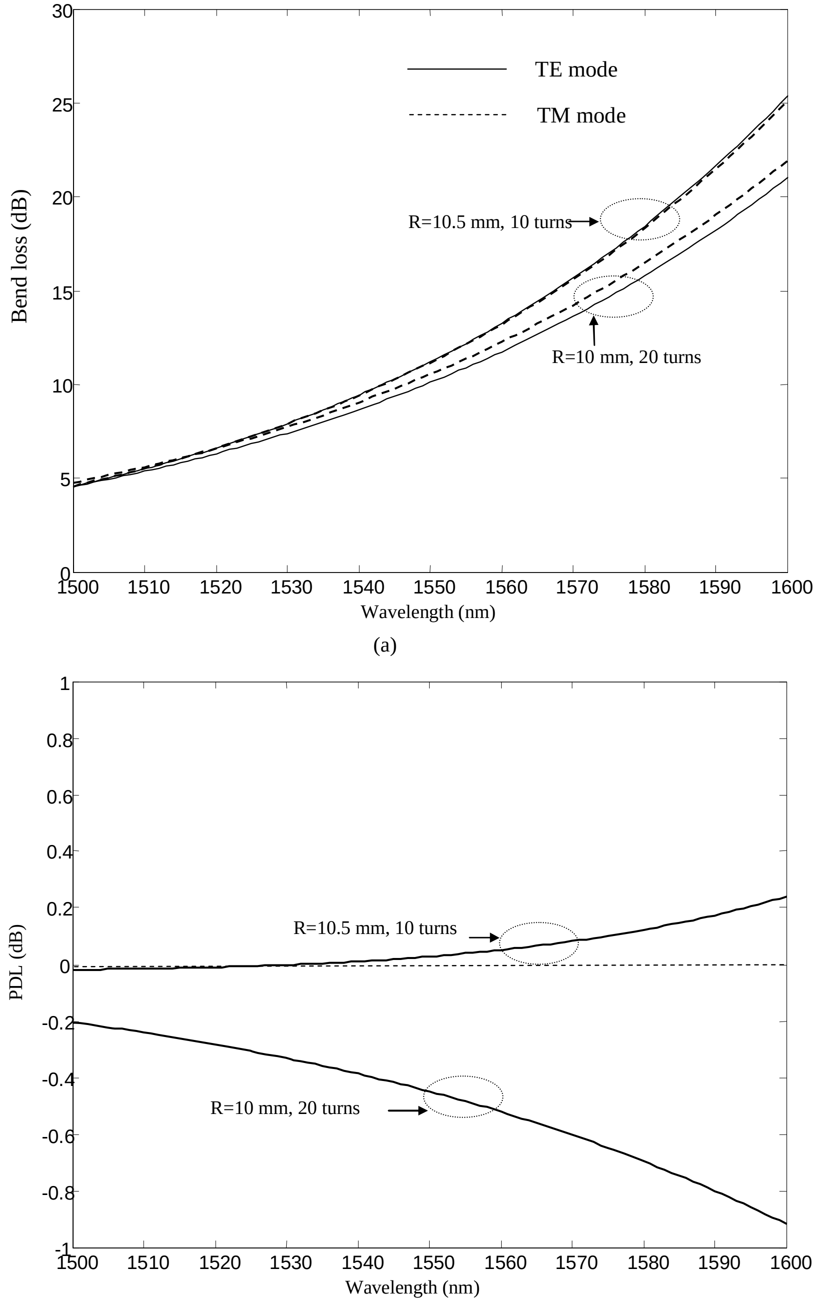
plotted in Fig. 3(b) are significantly different. From Fig. 3(b) it can be seen that the PDL for case 1 is bigger than that of case 2. So the polarization dependent loss with the traditional definition is not sufficient to characterize the polarization sensitivity of bend loss for different bending radii in a general sense, i.e., regardless detailed bending loss and bending length.



(b)

Fig. 3. (a). Bend loss for TE and TM mode of a bending fiber with radius 10 mm and length of 20 turns and a bending fiber with radius of 10.5 mm and length of 10 turns; (b) corresponding polarization dependent losses.

Therefore, a normalized polarization sensitivity is proposed by the following definition

$$PDL_N = 2\frac{Ls_{TE} - Ls_{TM}}{Ls_{TM} + Ls_{TE}} \tag{5}$$

With this formula, the polarization sensitivity for a bending radius can be characterized in a general sense without referring to a detailed bend loss or bending length. In a practical situation, the polarization dependent loss can also be easily estimated providing the bend loss of the fiber is known.

For the first calculation example, the polarization sensitivity for different bending radii at a wavelength of 1550 nm is presented in Fig. 4. Compared to the Fig. 2(b), this normalized polarization dependence can predict the polarization sensitivity for different bending radii accurately. For example, in Fig. 4, the polarization dependence for bending radius of 10 mm is much higher (here the absolute value is referred) than that for bending radius of 10.5 mm, which has been verified in Fig. 3(b).

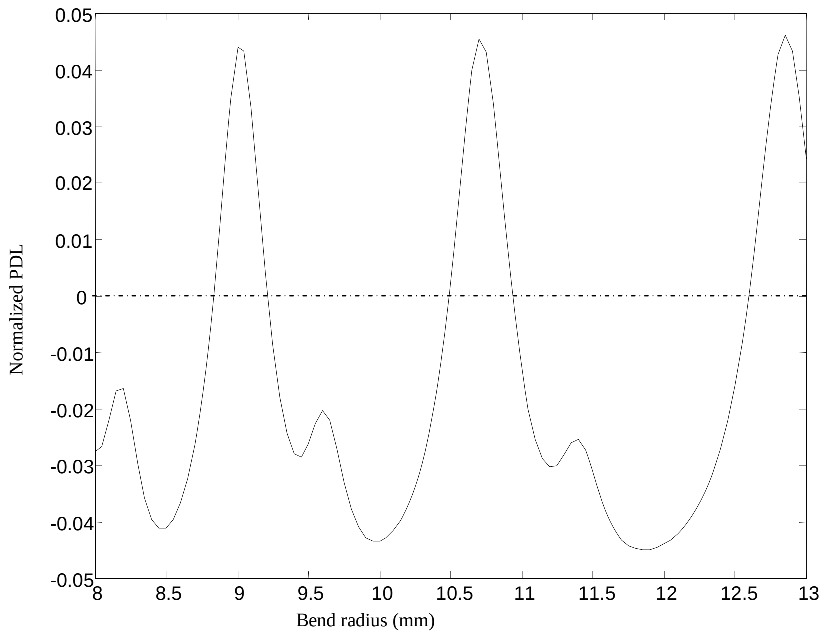


Fig. 4. Normalized polarization dependent loss for different bending radii.

The normalized polarization dependence shown in Fig. 4 shows that the polarization sensitivity of SMF28 has a quasi-periodical characterization with bending radius and this quasi-periodical characterization is very close to that of the bend loss vs bending radius as shown in Fig. 2(a). However, in Fig. 2(a), it can be seen that although because of the whispering gallery mode, the bend loss does not decrease monotonically as the bending radius increases; but it still shows a decreasing trend. For example, the bend loss for bending R=9 mm and R=10.7 mm are both on the peaks of the curve, but the bend loss the bend loss for bending radius of 9 mm is much bigger than that of R=10.7 mm. As distinct from the bend loss, the normalized polarization dependence in Fig. 4 has no such trend, which means that for bending radius R=9 mm and R=10.7 mm, they will have the same polarization dependent loss when they have the equivalent bend loss.

To verify the polarization sensitivity of the bending fiber, corresponding experiments are presented below.

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3. Experimental results

The polarization dependence of the bending fiber was measured for different bending radii and different wavelengths, respectively. Figure 5 gives the experimental setup used for our measurement of polarization dependence of fiber bend losses, which includes a tunable laser, a polarization controller, a bending fiber section and an optical spectrum analyzer.

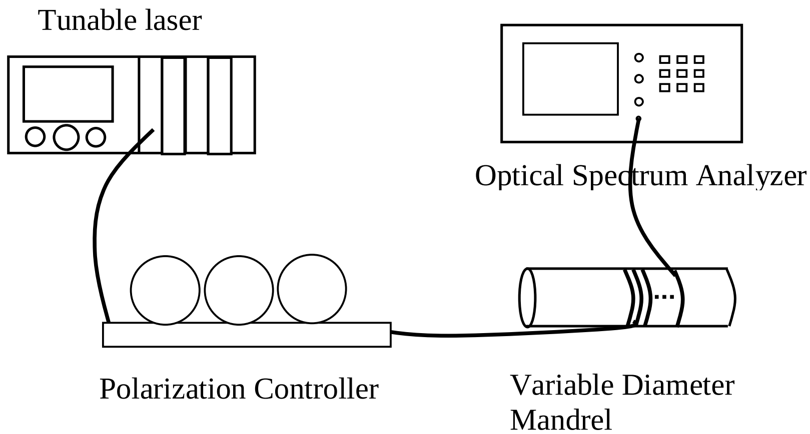

Fig. 5. Experimental setup for measuring polarization dependent loss.

First, the bend loss of the SMF28 was measured for the bending radius from 8 to 11.5 mm at a wavelength of 1550 nm without connecting the polarization controller. The bend loss for these bend radii with a length of 10 turns is presented in Fig. 6(a) and the calculated results are presented as well for a comparison. The experimental and theoretical results are in a satisfactory agreement. Both results show the influence of the coating layer on the bend loss, e.g., the bend loss does not decrease monotonically as the bending radius increases as mentioned above.

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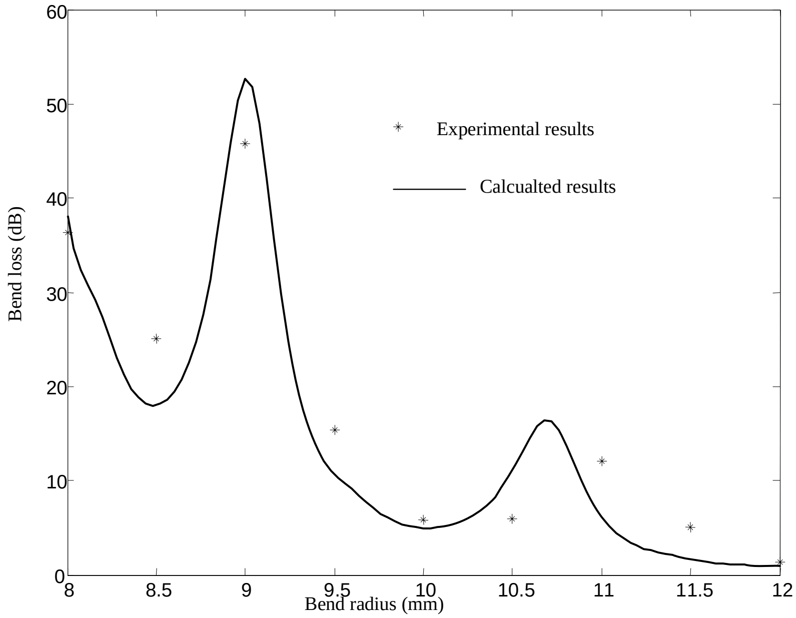
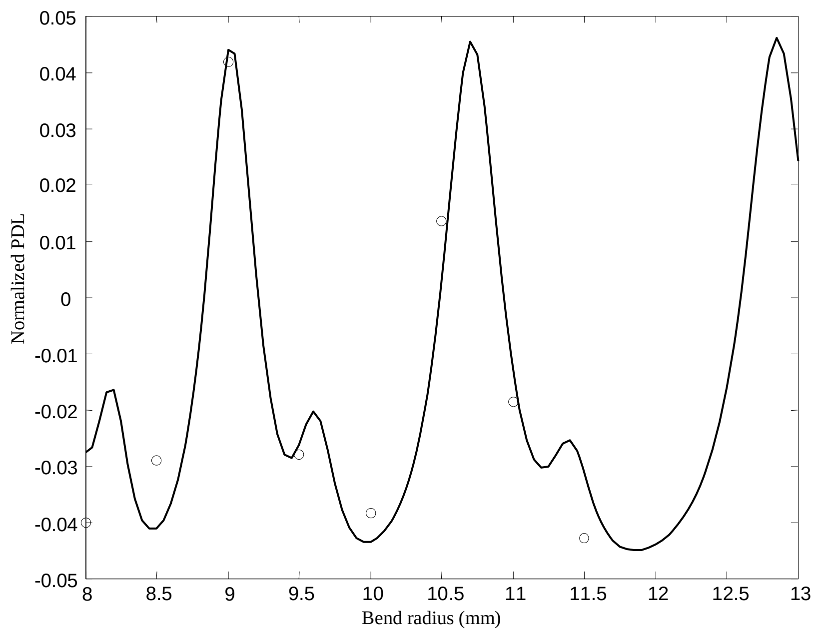


(a)



(b)

Fig. 6. (a). Measured bend loss of SMF28 at wavelength 1550 nm with a length of 10 turns; (b) normalized polarization dependent loss.

To investigate the polarization dependence of the bending fiber under different bending radii, the maximal and minimal values of measured bend loss are recorded while tuning the polarization controller. It is not possible to find out the respective bend loss for the TE and TM modes directly in this experiment with the polarization controller, which instead offers the maximal and minimal bend loss through adjusting the polarization controller. Therefore,

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the signs of the theoretical normalized polarization dependent loss are used as the reference for the experimental results. Corresponding results are presented in Fig. 6(b). From the figure one can see that the theoretical prediction have a good agreement with the measured normalized polarization dependent loss.

Finally, we investigated the polarization dependence of the bend loss for the bending fiber under different wavelengths. Corresponding to the simulation results presented in Fig. 3(b), the polarization dependent loss are measured for (a) a fiber with a bending radius of 10 mm and a length of 20 turns and (b) a fiber with a bending radius of 10.5 mm and a length of 10 turns. The measured polarization dependence over the wavelength range from 1500 to 1600 nm are presented in Fig. 7 with marks as squares and circles, respectively. For convenience, the calculated results of the PDL are also presented in Fig. 7 as the comparison. From Fig. 7 one can see the measured PDL for bending radius of 10 mm is bigger than that for the bending radius of 10.5 mm as predicted by the theoretical calculation. The calculated polarization dependent losses matched the measured results. The theoretical predicted results for the bending radius of 10.5 mm have a better agreement with the measured PDLs as compared to the case of 10 mm. The discrepancy between the calculated PDL and measured results could be caused by the approximations made in the calculation. Calculation of bend loss and polarization dependence for a singlemode fiber includes some approximations, e.g., the curved interface between the coating and cladding is treated as an infinite plane and the light field within the core is approximated by the unperturbed field of the straight fiber with infinite cladding as mentioned above. The calculated bend loss and polarization dependence has an overall agreement with the experimental results, i.e., they can not guarantee the accurate agreement for each bending radius due to its limited accuracy. This can also be seen in Fig. 6(b). For some bending radii, the calculated normalized PDL has a good agreement with the experiment but for some bending radii there is a discrepancy between the prediction and experiment. From Fig. 6(b), one can also see that the bend radius of 10 mm suffers a bigger discrepancy between the theoretical and experimental result as compared to the case for bending radius of 10.5 mm.

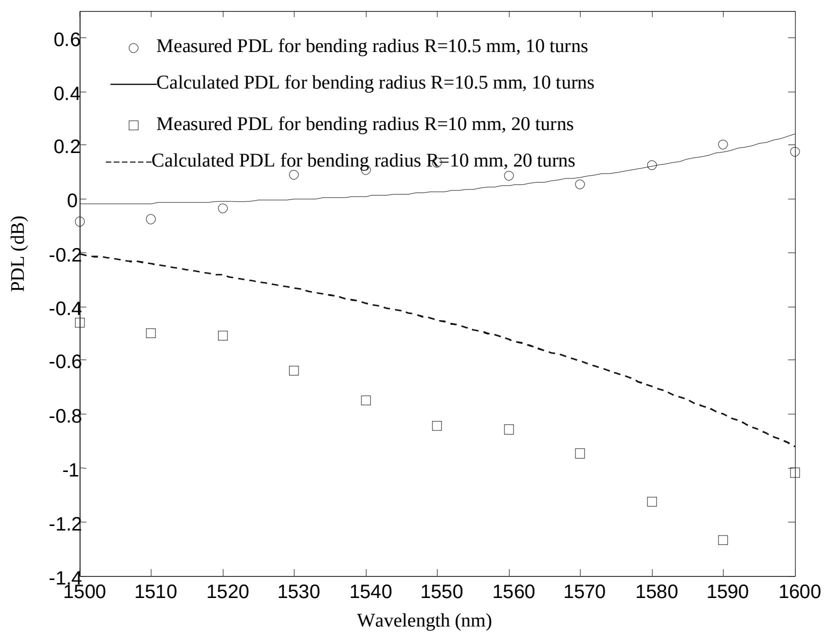

Fig. 7. Measured polarization dependent losses for bending radius of 10 (20 turns) and 10.5 mm (10 turns).

4. Conclusion

Polarization dependence of bend loss for the standard singlemode fiber has been investigated theoretically and experimentally. Calculation for the bend loss of a singlemode fiber for the TE and TM mode has been presented, considering the respective boundary condition at the interface between the cladding and coating layer. With the proposed normalized polarization dependent loss, the polarization sensitivity for different bending radii is characterized. Corresponding experimental results have been presented, which agree with the theoretical predictions. Both theoretical and experimental results have shown that the coating layer has a significant influence on the polarization dependence of bend loss.

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