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Investigation of Macrobending Losses of Standard Single Mode Fiber with Small Bend Radii

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Abstract

An investigation of macrobending loss characteristics of a standard singlemode fiber (SMF28) for small bend radii is presented theoretically and experimentally, which includes the bend loss of the SMF28 with coating layers and the bare SMF28 after stripping the coating layers and chemical etching of partial cladding. The significant influence of reflection occurring at the interface between the cladding and coating layer or the cladding layer and air on the bend loss is investigated theoretically and experimentally.

Keyword: Fiber macrobending loss, single mode fiber, whispering gallery mode

1. Introduction

Optical fiber has been used in a range of optical sensing applications involving microbending or macrobending [1-6]. Examples include displacement sensing [1], pressure sensing [2, 4], wavelength referencing sensing [3], temperature sensing [6], and so on. Theoretical investigations about macrobending loss of fibers started in 1970s. The models developed by D. Marcuse [7, 8] treated the fiber as a core-infinite cladding structure. For the core-cladding-infinite coating structure, a number of theoretical modeling and corresponding experimental investigations of macrobending loss have been presented in Refs. [9-13], which considered the impact of the whispering-gallery mode (WGM) caused by the reflection of the radiated field at the interface between the cladding and coating layer. Previous published investigations of fiber bend losses have been focused on some special fibers (particularly fibers with small numerical apertures) rather than standard single mode fibers (such as SMF28), which are widely used in optical communications [9-12].

Recently, the macrobending loss properties of SMF28 (bend radius ranges from 8.5 to 12 mm) were investigated theoretically and experimentally and optimized as an edge filter for wavelength measurements [14, 15]. However, a bending fiber with a smaller bend radius, e.g.,

substantially less than 10 millimeters, is useful for sensing applications, particularly when the fiber bend is optimized as a small optical probe. Therefore, it is necessary to study the characteristics of macrobending loss with smaller bend radii. In practice, after stripping the polymer coating layers, the bare fiber is easily broken without any protection. To reduce the bending induced internal stress and allow for smaller bending fiber structures, the fiber cladding is etched partially by using HF acid, which will be presented in Sec. 4.

A thorough investigation of the fiber bend loss with small bend radii is presented theoretically and experimentally, which includes: 1) theoretical modeling analysis for fiber bend loss; 2) macrobending loss of the SMF28 with coating layers; 3) macrobending loss for the bare SMF28 fiber after stripping the coating layers (core-cladding structure only) and partially etching the cladding layer; 4) macrobending loss of the bare etched SMF28 fiber after coating with an absorbing layer. The theoretical results agree with the measured bend losses for SMF28 with or without polymer coating layers. Through comparison between the first two cases and the third case, it is found that the whispering-gallery modes caused by reflection at the interface between the cladding and coating layer (case 1) or between the cladding layer and air (case 2) have a significant impact on the bend loss.

2. Theoretical modeling for fiber bend loss

There are different approaches developed for the prediction of the macrobending loss of singlemode fibers with coatings [10-12]. For example, a theoretical model based on weak perturbance of the guide field has been presented in Ref. [10-12]. Fig. 1 illustrates the cross section of a bend fiber with a core-cladding-infinite coating layer structure. Based on the weak-guidance approximation theory, when the fiber is bent the Fourier transform scalar field in the cladding and infinite coating regions in both x and y-direction can be expressed as a Fourier series following [10]:

$$\Psi(x,y)=\begin{cases}\sum_{p=1}^{N}\left\{C_p Bi[X_{2,p}(x)]+R_p Ai[X_{2,p}(x)]\right\}\cos\beta_p y & a\le x\le x_h\\ \sum_{p=1}^{N}D_p\left\{Bi[X_{3,p}(x)]-iAi[X_{3,p}(x)]\right\}\cos\beta_p y & b\le x<\infty\end{cases} \tag{1}$$

Assuming that bending takes place in the x-plane, β_p is the conjugate variable for the Fourier transform in the restricted narrow y-region, and β_p could be expressed as: $\beta_p=(2p-1)\pi/2h$ (p is positive integer, p=1, 2, …), and h is defined in Fig. 1. In our calculations, it is found that the calculated bend loss differs with the h value. A simple and practical method to find out a suitable h-value can be: 1) assume the refractive index of the coating to equal to that of the cladding, i.e., core-infinite cladding structure, 2) calculate the bend loss with the above method and the method developed by D. Marcuse in Ref. [7], separately under different bending radii. 3) determine a suitable h-value so that the two results match.

For the Corning standard SMF28 fiber considered in this paper, the refractive indices (for wavelength 1550 nm) and radii of the core, cladding and coating layers are shown in Table 1.

Fig. 2 shows the calculated fiber bend loss results from Ref. [7] and Ref. [10] for standard SMF28 fiber. For illustration values of h equal to 20 μm, 27.8 μm, and 40 μm for the y-direction are shown. From Fig. 2, one can see that the calculated result with h=27.8 μm (dashed line) from Ref. [10] is in agreement with the modeling result (solid line) from Ref. [7] and this yields a suitable value of h in the formula (1).

3. Fiber bend loss with coating layers

As mentioned in the introduction, the existence of the coating layer(s) will produce a so-called whispering-gallery mode for a bending fiber due to the reflection of the radiated field at the interface between the cladding layer and the coating layer. Previous published investigations of fiber macrobending loss have developed a series of formulas for the calculation of fiber macrobending loss, and when the effect of the coating layer is included the formulas presented in Ref. [10-12] are used. In this experiment, the singlemode fiber was wrapped on a mandrel consisting of multiple sections, each providing a different usable diameter. The bending fiber was connected to a tunable laser and an optical spectrum analyser. The bend losses of SMF28 fiber with an absorbing layer (to remove the reflection occurring at the interface between the coating layer and air) were measured for the bending radii range from 6 to 8.5 mm when the wavelength is 1500 and 1600 nm, respectively (see Fig. 3a and Fig. 3b).

One can see that as the bend radius increases, the non-monotonic decrease of both the experimental and theoretical results of the bend loss confirms the impact of a strong WGM influence caused by the coating layer as mentioned above. In Fig. 3, the modeling results agree well with the experimental data for a bend radius in the range from 7 to 8.5 mm. When the bend radius gets smaller, the agreement between the theoretical and experimental results decreases. One reason is that in the experiment for such cases, the bend loss is highly sensitive to the bend radius, e.g., the discrimination is about 40 dB between the bend radius 5.5 and 6 mm in Fig. 3b, however, in practice it is difficult to control the bend radius precisely.

4. Bend loss of a bare SMF28 after stripping coating layers and partially etching the cladding layer

In our experiments, the SMF28 fiber coatings were stripped by hot concentrated sulfuric acid (H_2SO_4, wt >95%, ~200°C). It is found that the fiber is easily broken even when the bend radius is smaller than 10 mm. To reduce the bending stress and retain the mechanical flexibility of bare fiber, the fiber cladding is etched partly by using hydrofluoric (HF) acid. After the etching process using HF acid and cleaning by acetone and alcohol, the diameter of thinned-cladding fiber was about 61 μm, measured by a high-precision screw micrometer. Both the bare SMF28 and the thinned-cladding fiber as seen under a microscope are shown in Fig. 4.

We measured the bend loss of the bare SMF28 fiber with a diameter of 61 μm, for a bend radius of 5.5, 6.0, and 6.5 mm (the bend length is one turn), in the wavelength range from 1500 to 1600 nm, and corresponding results are presented in Fig. 5. For this case, the reflection of the radiated field at the interface between the cladding layer and air has a significant impact on the bend losses. When the bending etched fiber without an absorbing

layer coated at the outside, the radiated light is reflected back at the interface between the cladding layer and air. The reflected light is coupled with the propagating light within the core. As distinct from the first case presented in section 3, where the radiated field is reflected at the interface between the cladding and coating layer, the reflection occurring in the case of etched fiber is much stronger due to the significant refractive index difference between the cladding and air (the etched fiber can be regarded as a multimode fiber when the cladding is treated as the core and the air is the cladding). Because of the strong reflection and recoupling, which can be seen from the simulation results by e.g., the beam propagation method, there is no single quasi-guided mode propagating within the core as the case of bending fiber with a polymer coating. This is why the measured bend loss presented in Fig. 5 seems "unusual", for example, from Fig. 5, one can see that the bend loss at 5.5 mm which increases with wavelength to one at 6.5 mm which decreases, whilst at 6mm the loss peaks at 1540 nm.

It should be noted that modeling of the behavior of the bare etched fiber using the technique outlined in section 2 is not possible. This can be explained as follows, for the case of core-cladding-infinite coating presented in the above section, in which the refractive index of coating layer is higher than that of the cladding there is only a single quasi-guided mode propagating in the bending fiber. However, for the bare etched SMF28, the refractive index of the cladding layer is higher than that of the surrounding air and the whole fiber can be regarded as a multimode fiber. The numerical beam propagation method shows the reflected field by the interface of cladding layer and air is strongly coupled with the guided mode within the fiber core along the direction of propagation. No single quasi-guided mode is observed as the case of core-cladding-coating structure (where the refractive index of coating is much higher than that of the cladding layer). For this case, the existing analytical expressions shown in section 2 are not suitable for modeling.

5. Bend loss for the core-cladding-absorbing layer structure

To remove the impact of the reflection at the interface between the cladding and air the bare thinned-cladding fiber was coated with an absorbing layer. This case is approximately equivalent to a core-infinite cladding structure and the analytical expression for calculating the fiber bend loss with an infinite cladding developed by D. Marcuse [7, 8] is used.

In the experiment, the etched section coated with absorbing layer, was bent to form a small 360° bend in free space, with the fiber overlapped in a "knot-like" fashion for mechanical stability, and the ends of fiber were connected with a tunable laser and an optical spectrum analyzer, respectively. The operating process is the same as the experiment which has been described earlier in Section 4. The theoretical and experimental macrobending loss curves versus wavelength range from 1500 to 1600 nm for bend radius of 6.5 and 6 mm are presented in Fig.6a and Fig. 6b, respectively, from which one can see that the theoretical bend loss agrees with the experimental results. As a comparison, the measured bend losses of bare SMF28 in Fig. 5 are also presented. The difference of bend loss between the two cases, i.e., bare SMF28 and the bare SMF28 with an absorbing layer, shows that the reflection occurring at the interface between the cladding layer and air has a significant effect on the bend loss.

6. Conclusion

In conclusion, we have presented a thorough theoretical and experimental investigation

of the macrobending loss characteristics of a standard singlemode fiber with small bend radii, which includes theoretical modeling analysis for fiber bend loss, for SMF28 with coating layers and the bare SMF28 after stripping the coating layers and chemical etching of partial cladding. Both experimental and theoretical results have demonstrated the impact of reflection occurring at the interface between the cladding and coating layer or the cladding layer and air on the bend loss.

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Figure Captions:

Fig. 1 The cross section view of the bend fiber with core-cladding-infinite coating structure

Fig. 2 Theoretical modeling bend loss curves from Ref. [7] (solid line) and Ref. [10] (the dashed line is with h=27.8 μm; the dash-dot line is with h=20 μm; the dotted line is with h=40 μm) for SMF28 fiber with different bend radii at the wavelength is 1500nm

Fig. 3a Modeling and measured macrobending losses for bend radius ranging from 6 to 8.5 mm at the wavelength of 1500 nm

Fig. 3b Modeling and measured macrobending losses for bend radius ranging from 6 to 8.5 mm at the wavelength of 1600 nm

Fig. 4 Photograph of etched thinned-cladding fiber contrasting against standard stripped bare SMF28 optical fiber

Fig. 5 Measured bend loss results of thinned-cladding SMF28 fiber without absorbing layer in wavelength ranging from 1500 to 1600 nm for bend radius is 5.5, 6.0, and 6.5 mm.

Fig. 6a Measured and modeling bend loss results for thinned-cladding fiber at wavelength range from 1500 nm to 1600 nm with bend radius is 6.5 mm with and without absorbing layer

Fig. 6b Measured and modeling bend loss results for thinned-cladding fiber at wavelength range from 1500 nm to 1600 nm with bend radius is 6 mm with and without absorbing layer

Table Caption:

Table 1 Parameters of the standard Corning SMF28 fiber; (the refractive index values are defined at a wavelength of 1550 nm)

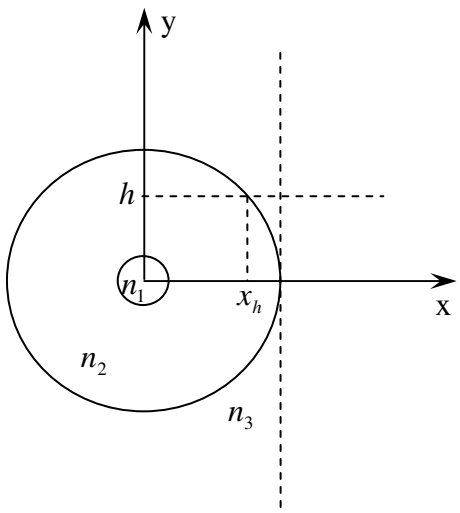


Fig.1 The cross section view of the bend fiber with core-cladding-infinite coating structure

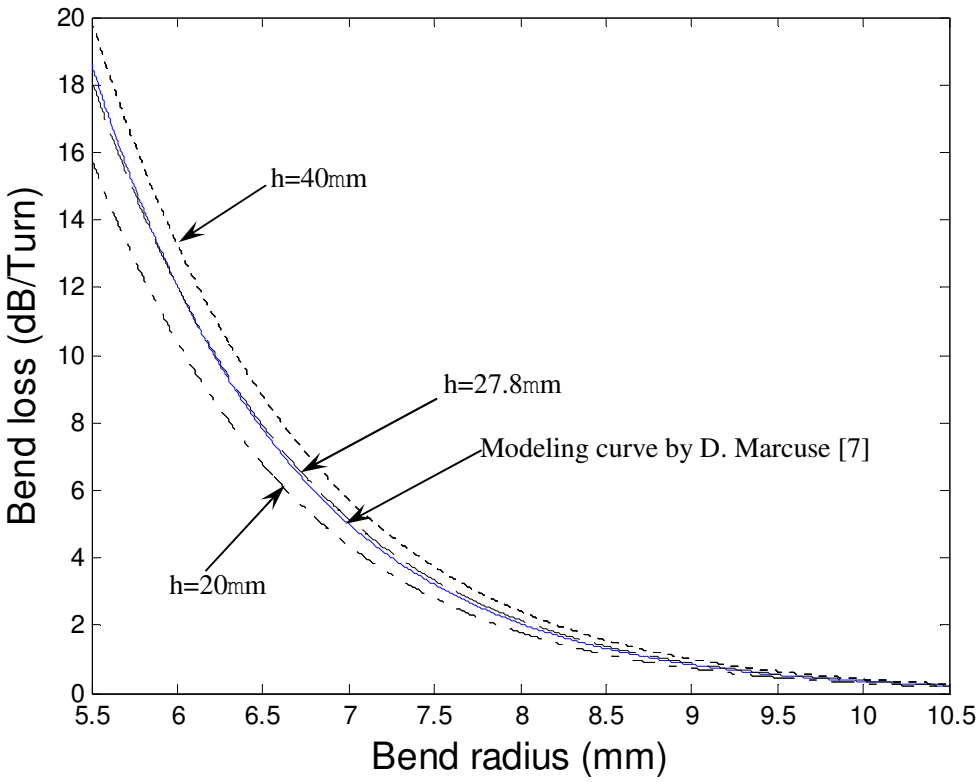
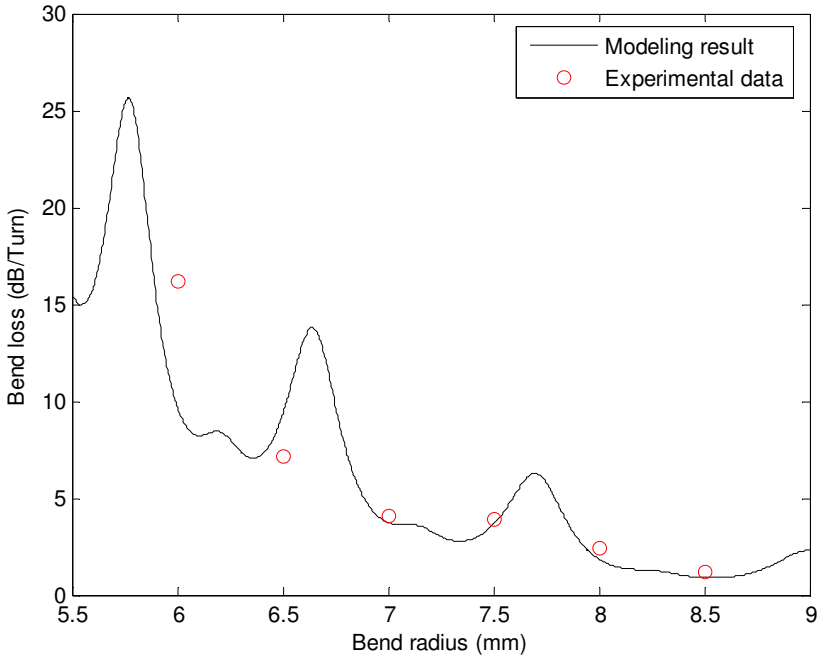
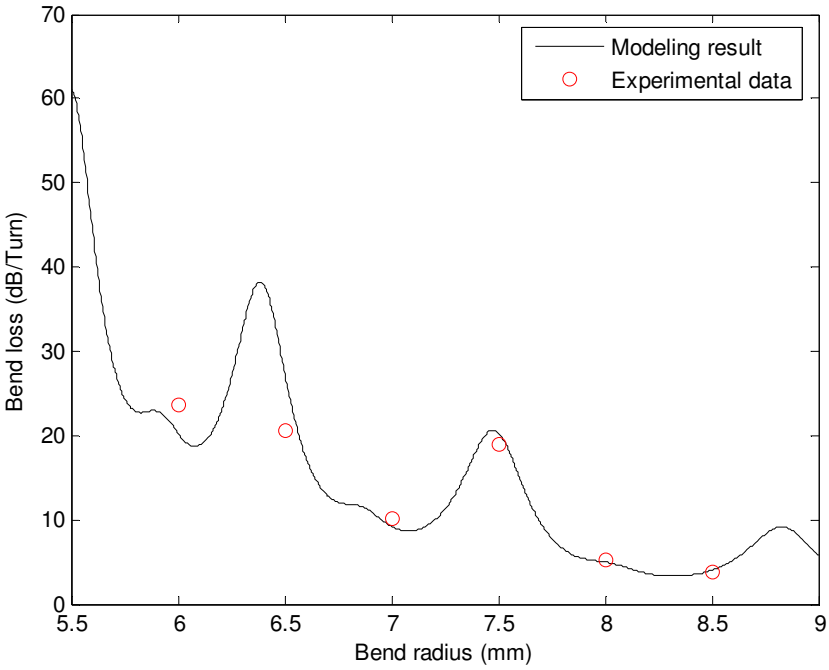


Fig.2 Theoretical modeling bend loss curves from Ref. [7] (solid line) and Ref. [10] (the dashed line is with h=27.8mm; the dash-dot line is with h=20mm; the dotted line is with h=40mm) for SMF28 fiber with different bend radii at the wavelength is 1500nm


Modeling result
Experimental data
Bend loss (dB/Turn)
Bend radius (mm)
0
5
10
15
20
25
30
5.5
6
6.5
7
7.5
8
8.5
9

(a)



(b)

Fig.3 Modeling and measured macrobending losses for bend radius ranging from 6 to 8.5 mm at wavelength a) 1500 nm b) and 1600 nm

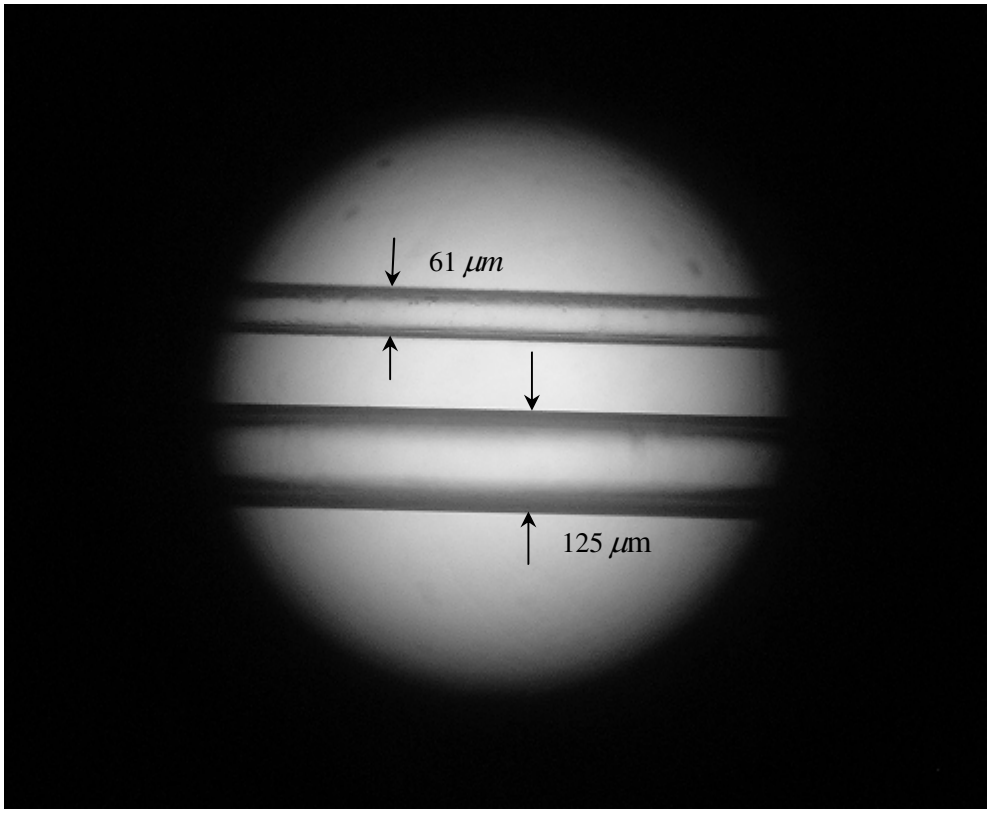


Fig. 4 Photograph of etched thinned-cladding fiber contrasting against standard stripped bare SMF28 optical fiber

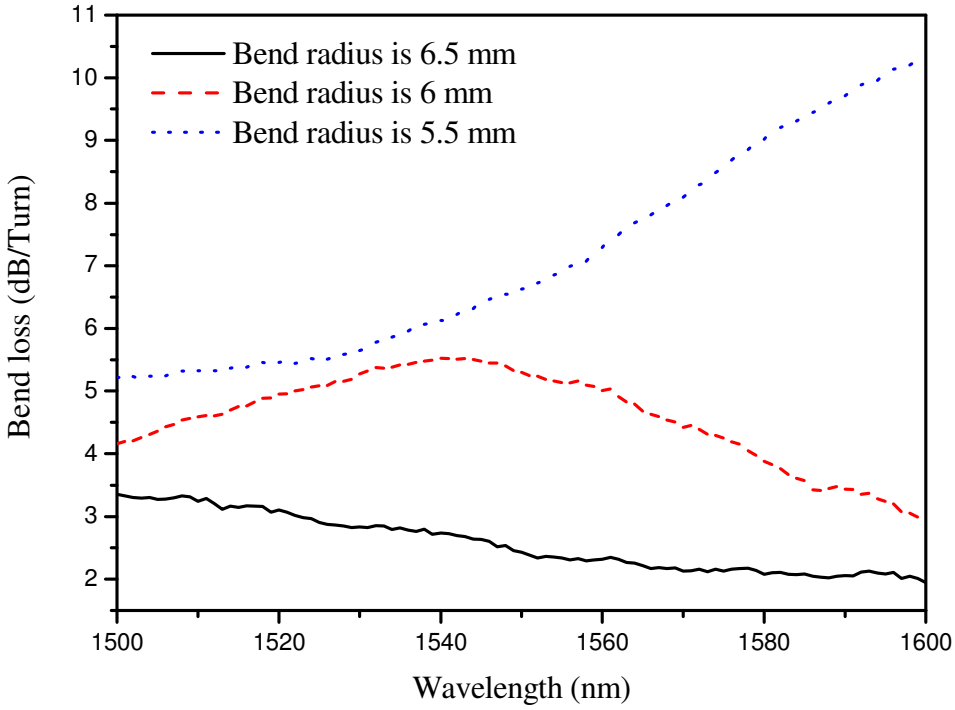
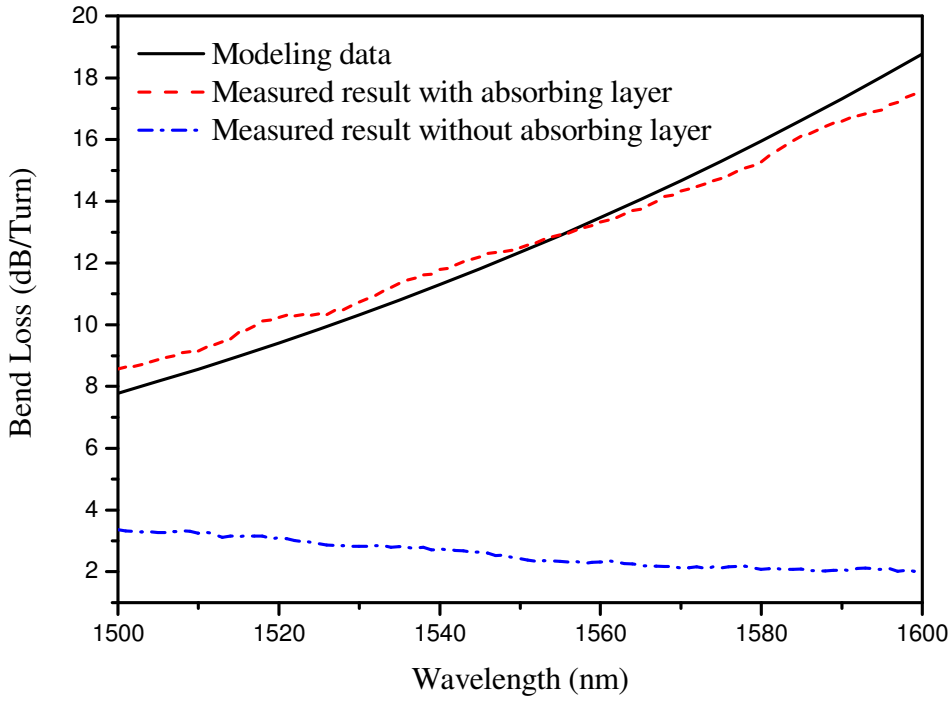
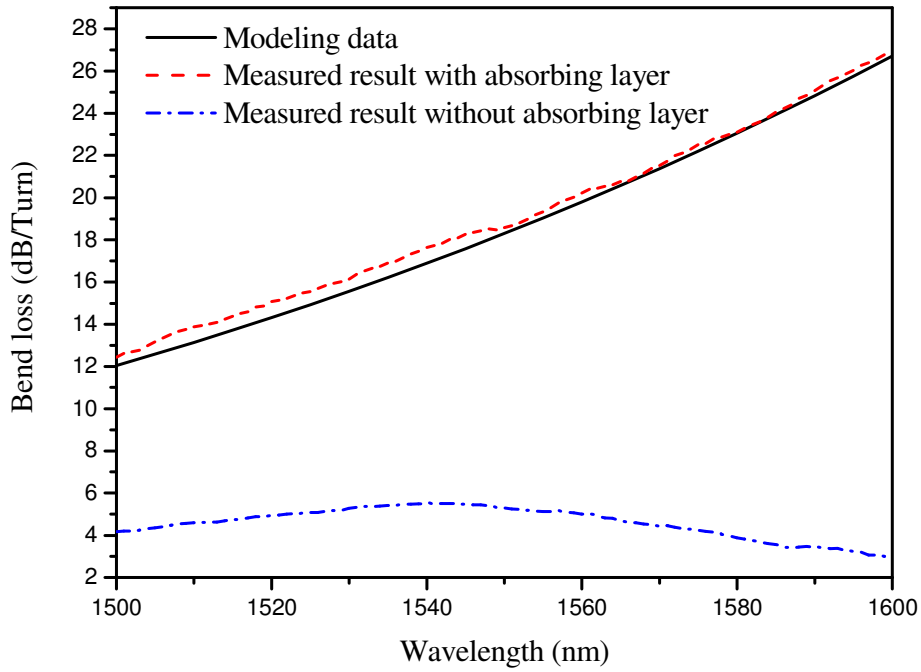


Fig. 5 Measured bend loss results of thinned-cladding SMF28 fiber without absorbing layer in wavelength ranging from 1500 to 1600 nm for bend radius is 5.5, 6.0, and 6.5 mm.


Modeling data
Measured result with absorbing layer
Measured result without absorbing layer
Bend Loss (dB/Turn)
Wavelength (nm)
20
18
16
14
12
10
8
6
4
2
1500
1520
1540
1560
1580
1600

(a)



(b)

Fig. 6 Measured and modeling bend loss results for thinned-cladding fiber at wavelength range from 1500 nm to 1600 nm with bend radius is a) 6.5 mm b) and 6 mm with and without absorbing layer

SMF28 fiber	Refractive index	Radius (μm)
Core	n_1=1.4504	a=4.15
Cladding	n_2=1.4447	b=62.5
Inner coating	n_3=1.4786	c=95
Outer coating	n_4=1.5294	d=125