Theoretical and experimental investigations of macro-bend Losses for standard single mode fibers

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Abstract: Modeling of macro-bend losses for single mode fibers with multiple cladding or coating layers is presented. Macro-bend losses for standard single mode fibers (SMF28) are investigated theoretically and experimentally, showing that the inner primary coating layer of SMF28 has a significant impact on the bend losses and most of the radiation field is absorbed in the inner primary coating layer of SMF28. The agreement between theoretical calculations and experimental measurements suggests that the so-called elastooptical correction in modeling is not required for SMF28.

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 single mode fiber is bent. Accurate modeling of this bend loss is essential for the design of fibers employed in optical communications or optical devices based on a bent fiber, such as some forms of optical sensor [1]. The simplest model treats a bent fiber as a core-infinite cladding structure [2,3]. In fact, a practical fiber with coating layer(s) offering mechanical protection shows quite different bend loss characteristics to those predicted by the simplest model. Existing theoretical calculations of fiber bend losses treat a fiber as a core-cladding-infinite coating structure, when considering the impact of coating layer [4-7]. As we know most fibers have double coating layers or some fibers themselves have more than one cladding layer, such as depressed-cladding fibers but no existing formulas have been presented for modeling bend losses of these fibers except the prediction of maximum or minimum bend losses conditions in relation to fiber parameters and input wavelength [8,9]. Therefore, calculation of bend losses for a single mode fiber with multiple cladding layers or coating layers based on perturbation theory is firstly presented in Section 2, which can be used for simulation and design of fiber devices with multiple cladding layers or multiple coating layers when macro-bend losses are involved.

Previous published investigations of fiber bend loss 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. In the present paper, the bend loss characteristics of SMF28 are investigated theoretically and experimentally. The impact of three interfaces: 1) between cladding layer and inner primary coating layer; 2) between the inner primary coating layer and outer primary coating layer and 3) between the outer primary coating layer and air on bend losses are analyzed. Detailed comparisons between the experimental measured results and theoretical calculated bend losses based on different models are carried out in Section 4, which indicate that most of the radiated field is absorbed in the inner coating layer and a theoretical model with only the inner coating layer can predict bend losses with a good agreement with experimental results. An elastooptical correction or so-called effective bending radius was required in previous published investigations in order to make the calculated bend losses agree with experimental results, due to the refractive index change caused by the bending stress. However, the agreement between theoretical and measured results in the present paper suggests that this elastooptical correction is not required for SMF28.

2. Theoretical calculations of fiber bend loss

Total loss of a bent fiber includes the pure bend loss in the bent section and the transition loss caused by the mismatch of propagation mode between the bent and the straight sections. For a single mode bent fiber of length L, the pure bend loss can be calculated by [8]

$$L_s = 10\log_{10}\left(\exp\left(2\alpha L\right)\right) = 8.686\alpha L \tag{1}$$

where α is the so-called bend loss coefficient, which is determined by the fiber structure, bending radius and wavelength of the light. Most theoretical investigations on fiber bend losses are focused on calculations of this bend loss coefficient.

The simplest model treats the fiber as a core-infinite cladding structure and a simple formula was developed to calculate the bend loss coefficient α [2]. A practical fiber contains one or two coating layer(s) outside to offer mechanical protection. The existence of the coating layer(s) will produce a so-called whispering-gallery mode for a bent fiber due to the reflection of the radiated field at the interface between the cladding layer and the coating layer. In order to consider the effect of this reflection on the bend loss, more complicated formulas for the bend loss coefficient α have been developed. Calculation of bend loss considering the coating layer was presented in Ref. [4] using perturbation theory, and subsequently two straightforward formulas were presented in Ref. [6] and [7], respectively. However, all these calculations are based on a fiber containing only one coating layer. Many fibers have more than one coating layer or the fiber itself may have a multiple cladding layer structure, for which the bend loss cannot be calculated with these formulas. Therefore, calculation of bend losses for a fiber with multiple cladding or coating layers using perturbation theory is presented below through generalizing the approach employed in Ref. [4] and [7], and it can be used for modeling and design of fiber devices with multi-cladding layers involving or utilizing bend loss. In common with previous models, the outermost layer is considered infinite in present calculation.

Figure 1 gives the schematic cross-section view of a bent fiber with multiple cladding or coating layers. The bending radius is denoted by R. For the q-th cladding layer, the refractive

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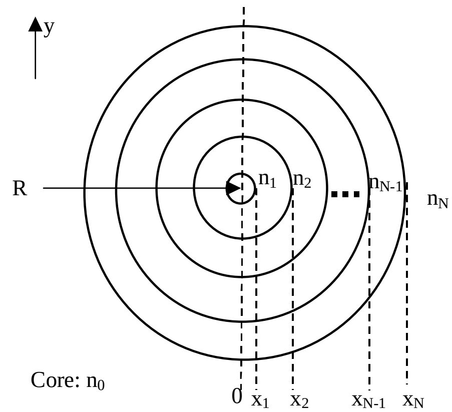

Fig.1. Cross-section of a bent fiber with multiple cladding layers.

index is n_q and the thickness is $x_{q+1} - x_q$. Based on the approximations made in Refs. [4-7], the field in the cladding layers of the bent fiber is

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

where the notation in Refs. [6] and [7] is used and $X(x,\zeta) = \left(\frac{R}{2k^2 n_q^2}\right)^{2/3}\left[\beta^2 + \zeta^2 - k^2 n_q^2\left(1 + \frac{2x}{R}\right)\right]$. B_i and A_i are Airy functions, respectively. For the outermost infinite layer, there is a relationship between $D_N(\zeta)$ and $H_N(\zeta)$, namely, $H_N(\zeta) = -jD_N(\zeta)$. For any two adjacent layers, according to field-continuous boundary conditions, we have

$$\begin{cases} D_q(\zeta)B_i\left[X_q(x_q,\zeta)\right] + H_q(\zeta)A_i\left[X_q(x_q,\zeta)\right] = D_{q+1}(\zeta)B_i\left[X_{q+1}(x_q,\zeta)\right] + H_{q+1}(\zeta)A_i\left[X_{q+1}(x_q,\zeta)\right] \\ D_q(\zeta)B_i'\left[X_q(x_q,\zeta)\right] + H_q(\zeta)A_i'\left[X_q(x_q,\zeta)\right] = D_{q+1}(\zeta)B_i'\left[X_{q+1}(x_q,\zeta)\right] + H_{q+1}(\zeta)A_i'\left[X_{q+1}(x_q,\zeta)\right] \end{cases}. \tag{3}$$

Therefore $\begin{bmatrix} D_1(\zeta) \\ H_1(\zeta) \end{bmatrix} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}\begin{bmatrix} D_N(\zeta) \\ H_N(\zeta) \end{bmatrix}$, considering all the cladding layers, or in a short form $D_1(\zeta) = GH_1(\zeta)$ consequently.

Based on the boundary condition between the first cladding layer and the core layer [7], we have $H_1(\zeta) = \frac{\pi}{\{GB_i[X_1(x_1,\zeta)] + A_i[X_1(x_1,\zeta)]\}(\gamma^2 + \zeta^2)^{1/2}}\exp\left[-a\left(\gamma^2 + \zeta^2\right)^{1/2}\right]$ and with the perturbation theory, the bend loss coefficient can be calculated by

$$2\alpha = -2\frac{\kappa^2}{2\pi\beta V^2 K_1^2(a\gamma)}\operatorname{Im}\left(\int_{-\infty}^{\infty} H_1(\zeta)A_i[X_2(0,\zeta)]d\zeta\right) \tag{4}$$

The advantage of this model is that it can not only be used to calculate bend losses of fibers containing only one coating layer as presented in Ref. [5-7], but also it is suitable for fibers with multiple cladding layers (depressed-cladding fibers) or coating layers. The fiber used in

Ref. [9] has two coating layers and the presented experimental results and theoretical investigations (predicting the maximum or minimum bend losses conditions in relation to fiber parameters and input wavelength) in Ref. [9] show that for that fiber, the radiated field penetrates through both the inner and the outer primary coating layers. With the above formulas, theoretical modeling, including the outer primary coating, shows a better agreement between the experimental and theoretical results, by comparison with the case where only the inner layer is considered.

3. Experimental investigations about bend losses for SMF28

Figure 2 gives the experimental setup used for our measurement of fiber bend losses. The optical spectrum analyzer is used instead of an optical power meter because it can measure the bend loss at the peak output wavelength of the tunable laser rather then over a range of wavelengths. The fiber used in the experiment is SMF28, which is a very common fiber and widely used in optical communication systems. It has core, cladding, inner and outer primary coating layers. Corresponding parameters are presented in Table 1.

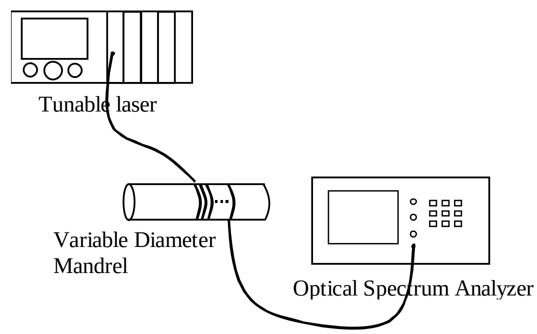

Fig. 2. Experimental setup for measuring fiber bend loss

Table 1. Parameters of SMF28 at wavelength 1550nm

n1	1.4504	2a	8.3μm
n2	1.4447	2b	125±0.7μm
n3	1.4786	2c	190μm
n4	1.5294	2d	250±5μm

Using a bending fiber of length 1~2 m, we measured the bend loss in the bend radius range of 8.5 mm to 12 mm inclusive, in increments of 0.5 mm and in the wavelength range from 1500 nm to 1600 nm. For bend radius smaller than 8.5 mm, the bend fiber is easily broken while for a bending radius larger than 12 mm, the bend loss is too low for reliable and repeatable measurement.

Figure 3 presents typical measured bend losses for SMF28 with or without an absorbing layer applied to the outside of the fiber. The curves for bend losses for a fiber without an absorbing layer outside have random variations that are small relative to the absolute bend loss at a given wavelength. The maximal variation in Fig. 3 is 3dB when the bend loss is 18dB. Further the measured results are not exactly repeatable and differ each time (Fig. 3 gives bend losses for ten measurements). After we coated the fiber with an absorbing layer,

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these random variations disappear and the measured bend losses also become invariant. This indicates that these random variations are caused by the reflection that occurs at the interface between the outer primary coating layer and air. It also shows that most of the radiated field is absorbed in the coating layers. Only a small amount of radiated field reaches the fiber surface and is reflected back resulting in interference with the propagation mode. Otherwise, according to the measured results and analysis method presented in Ref. [9], the curve for bend losses as a function of wavelength should have a periodical oscillatory nature comparable in amplitude to the bend losses themselves due to the reflection of the interface between the outer primary coating layer and air rather than these small random variations in our experiments.

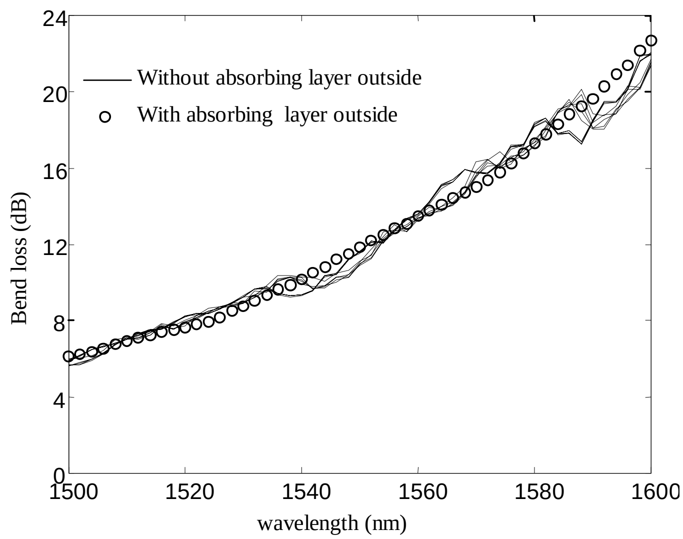


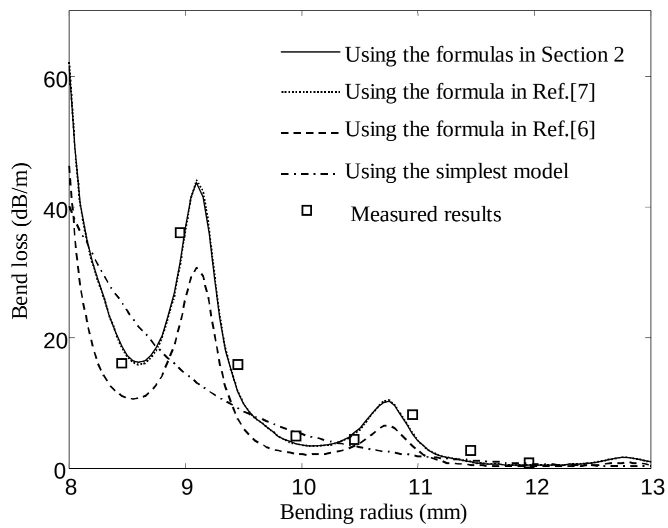
Fig. 3. Measured bend losses for bending radius R=10.5 mm and bent length of 0.66 m.

4. Comparisons between theoretical and experimental results

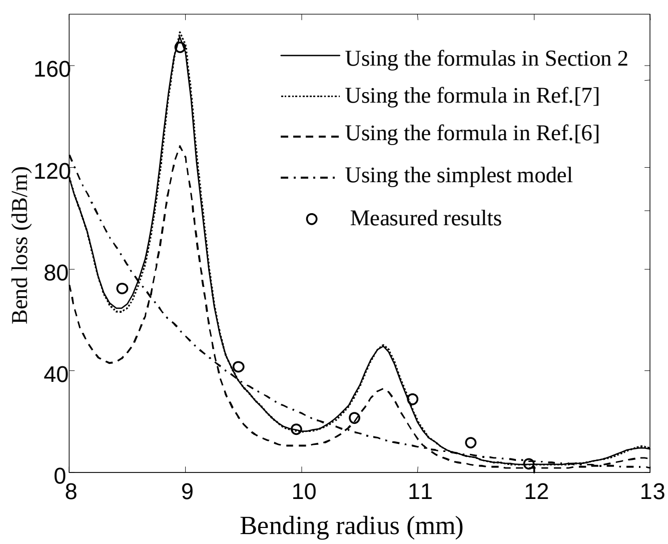
Detailed comparisons between theoretical and experimental results have been carried out in this section to investigate the accuracy of different models; the impact of the coating layers on bend losses and the so-called elastooptical corrections for modeling in the previously published investigations.

Initially, for the purpose of comparison with previous works, we treat the inner primary coating layer to be infinite, which is also equivalent to the case that the inner primary coating layer absorbs most of radiated field. Typical measured bend losses for different bending radii under two different wavelengths, i.e., 1500 nm and 1600 nm are given in Fig. 4(a), and 4(b) with squares and circles, respectively. Theoretical calculation results based on the simplest model (core-infinite cladding layer structure), the formulas proposed in Ref. [6] and [7] and the formula presented in the above section (all treat the fiber as a core-cladding-infinite coating layer structure in this calculation) are presented in Fig. 4(a) and Fig. 4(b).

From Fig. 4(a) and 4(b), firstly one can see the coherent coupling between the fundamental propagation field and the reflected radiated field by the coating layer, i.e., so-called whispering-gallery mode, has an apparent effect on bend loss characteristics so that the calculated results with the simplest model, i.e., treating the fiber as the core and infinite cladding structure, are obviously different from the measured bend losses. Simulation results with the formula proposed in Ref. [6] predicts the impact of the whispering-gallery as compared to the simplest model, but it still cannot agree with the measured results well due to the approximations made in deriving this formula. Calculated results with the formula developed in Ref. [7] and formulas presented in Section 2 have a good agreement with the experimental results and therefore, calculated results based on the presented formulas in Section 2 are used in the following comparisons.



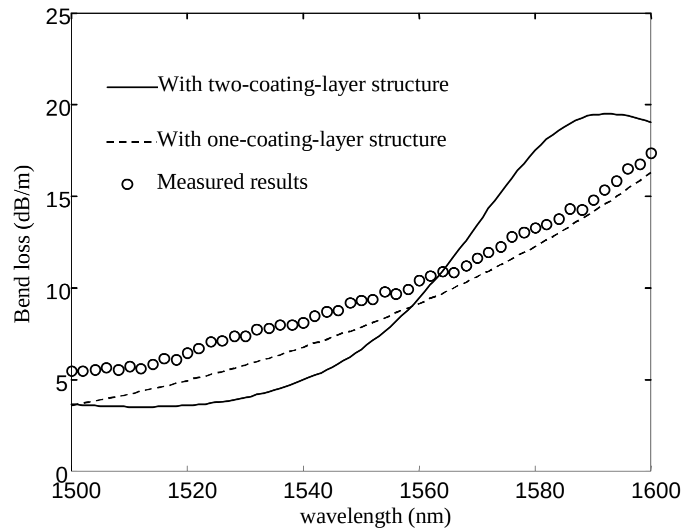
(a)



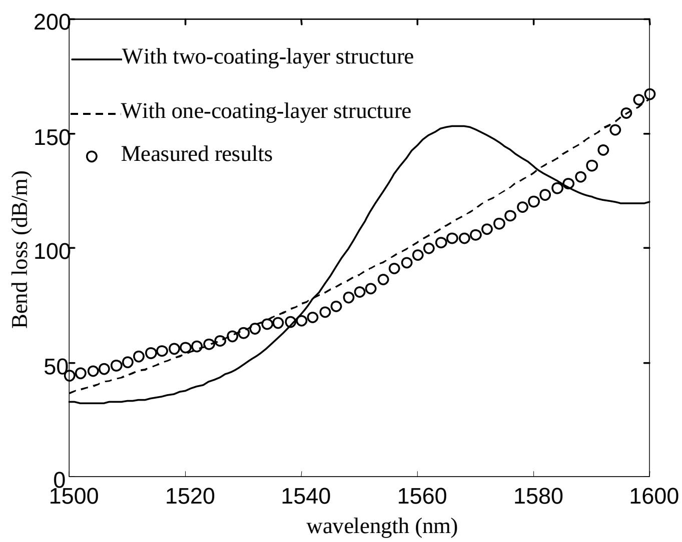
(b)

Fig. 4. Measured and calculated bend loss for different bending radii at wavelength a) 1500 nm and b) 1600 nm.

The agreements between experimental measured bend losses and calculated results in Fig. 4 also suggest that the inner primary coating layer absorbs most of the radiated field and the outer primary coating layer has little impact on the bend loss characteristics. In order to verify it, we carry out the calculation of bend losses considering the outer primary coating layer with the formula presented in Section 2, which has the advantage that it can calculate bend losses for more than one coating layer. The calculation treats that the inner primary coating layer as ideally transparent and the outer primary coating layer to be infinite. Figures 5(a) and 5(b) present the corresponding bend losses in wavelength range from 1500 nm to 1600 nm for bending radii R=9 mm and R=10 mm, respectively. The measured bend losses and the calculated results considering only the inner coating layer are also presented in Fig. 5 for comparison. From Fig. 5(a) and 5(b), one can see, that the calculated bend losses considering only the inner coating layer are much closer to the experimentally measured results. The existence for a two coating layer structure of a wave-like variation in the bend loss of the fiber with wavelength is mainly caused by the reflections at the interface between the inner and outer coating layers. The fact that the measured results do not display this wave-like variation support a conclusion that the inner coating layer absorbs most of the radiated field from the cladding.



(a)



(b)

Fig. 5. Calculated (with one-coating layer and with two-coating layers, respectively) and measured bend losses in wavelength range from 1500 nm to 1600 nm for a) for R= 10 mm and b) R=9 mm.

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In the previous published investigations, the elastooptical correction or a so-called effective bending radius was required in order to make the calculated bend losses agree with experimental results [5-7,10,11], due to the refractive index change caused by the bending stress. Generally the relationship between effective bend radius R_{eff} in modeling and actual bend radius R in experiments is $R_{eff} =\sim 1.27R$ and this correction is applied in modeling bend losses under whatever bending radii and wavelengths. We calculated the examples presented in previously published investigations with the formula developed in Ref. [7] and formulas presented in Section 2, respectively. It shows that numerical results using effective bending radius agree better with the measured bend losses than those obtained using actual bending radius directly. However, in the above calculations the agreement between theoretical and measured results for SMF28 suggests that this elastooptical correction is not required, i.e., $R_{eff} = R$. Theoretical bend losses for SMF28 with the so-called effective bending radius $R_{eff} =\sim 1.27R$ are presented in Fig. 6(a) and Fig. 6(b) with solid lines for wavelength range from 1500 nm to 1600 nm and bending radii 9 mm and 10 mm, respectively. Corresponding measured results and calculated results based on the same bending radii as those in experiments are also shown in Fig. 6(a) and 6(b). From this comparison one can see that it will lead to incorrect results if the effective bending radius is used in modeling bend loss for SMF28 as compared to the measured results. This suggests that in the present experiment the bending stress has little effect on the refractive index, so that the so-called effective bending radius for SMF28 almost equals to the actual bending radius. This could be caused by two reasons. One reason could be the fiber material itself and the other could be the fiber parameter *V*. Compared to the fibers used in the previously published investigations about macrobend losses, a significant difference is that in the present paper, the fiber parameter *V* of SMF28 is bigger than those of the fibers used in previous papers. For example, fiber parameter *V* of the fiber LB1000 employed in Ref. [7] is 1.68 (The considered bending radius is from 13.5 mm to 24 mm.). However, for the SMF28 used in the present paper the corresponding fiber parameter *V* is about 2.123 (The considered bending radius is from 8.5 mm to 12 mm). Further experimental and theoretical investigations about elastooptical correction for fiber bend loss are ongoing.

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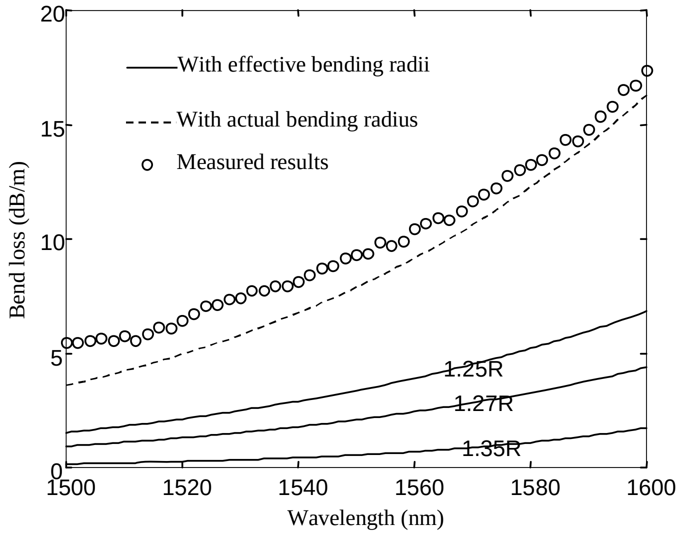
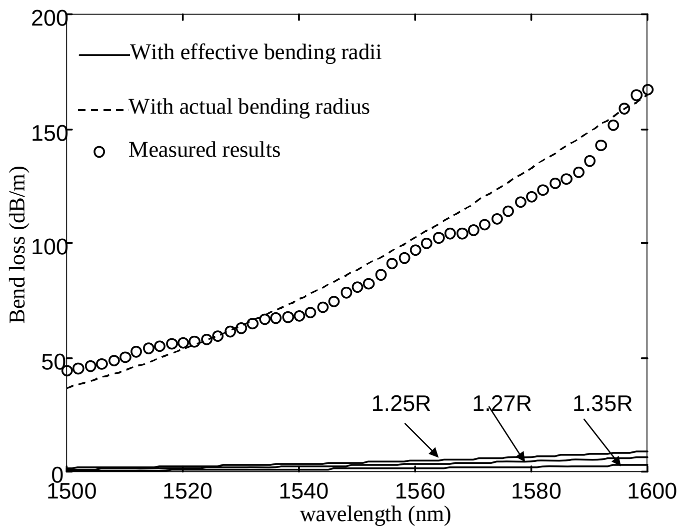


(a)



(b)

Fig. 6. Calculated (with and without elastooptical correction) and measured bend losses in wavelength range from 1500 nm to 1600 nm for a) for R= 10 mm and b) R=9 mm.

5. Conclusion

Modeling of bend losses for a single mode fiber with multiple cladding layers has been presented. Bend loss characteristics of the SMF28 have been investigated theoretically and experimentally. Both experimental and theoretical results have shown that reflection at the interface between the cladding layer and the coating layer has apparent effect on the bend loss characteristics. Comparisons between the experimental and theoretical results have indicated that: 1) most of the radiated field is absorbed in the inner coating layer and a theoretical model with only one coating layer structure agrees well with the experimental results. 2) The agreement between theoretical results and measured results suggests that so-called elastooptical correction used in previous published investigations is not required for SMF28.

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