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Generalised Design Process for Fiber-bend-loss-based Edge Filters for a Wavelength Measurement System

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Generalized design process for fiber bend loss based edge filters for a wavelength measurement system

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Abstract: A generalized methodology for the design of a fiber bend loss based edge filter is investigated and presented, starting with the task of evaluating and selecting suitable fibers and then considering the design of fiber bending loss edge filter. As an example to illustrate the methodology, a Corning SMF28e fiber with a 900 μm diameter is selected and two sample edge filters are designed for experimental verification. The designed edge filters are compact, easy to fabricate, meet target spectral specifications and show low PDL, confirming the effectiveness of the proposed methodology for fiber bend loss based edge filter design.

OCIS codes: (060.2310) Fiber optics; (060.2430) Fibers, single-mode; (120.2440) Filters.

1. Introduction

It is well known that macrobending loss occurs when an optical fiber is bent, and such fiber macrobending losses have been widely investigated as an important issue in optical fiber communications and sensing applications in recent decades [1-4]. The wavelength dependence of macrobending loss can be employed in an all-fiber based edge filter systems for rapid wavelength measurement in Dense Wavelength Division Multiplexing optical communication systems and in optical sensing applications [5-10]. In this regard a fiber bend loss filter based on low bend loss fiber (such as SMF28) has recently been investigated theoretically and experimentally for application in a ratiometric wavelength measurement system. The filter had a bending radius around 10 mm and multiple turns with a length circa 1~2 meters [5-7]. For such a filter both calculated and measured results showed that the fiber coating layers have a significant influence on polarization dependent loss (PDL) [8], which could reduce the precision of wavelength measurement. In order to ensure accuracy in wavelength measurement, low polarization dependence for the bend loss is required. As reducing the length of the fiber will reduce polarization dependence, using a bend sensitive fiber is one possibility to improve accuracy. Such a fiber bend loss filter based on bend loss sensitive fiber (1060XP fiber was used as an example) has been presented, demonstrating reduced PDL, using a bending radius of 10.5 mm and single turn structure [9], compared to 22 turns for an SMF28 based filter. In this case the fiber was stripped of its coating and an absorbing layer was applied to eliminate the development of whispering gallery modes (WGMs) at the glass-air interface. This is necessary as WGMs can result in a bend loss spectral response for the filter that is not monotonically increasing and is unusable in a wavelength measurement application.

However there are disadvantages to using a bare bend-sensitive fiber. Firstly a single loop structure is not mechanically reliable without the protection of polymer coating(s). Secondly discrepancies in fiber core size and NA between conventional fibers and 1060XP fiber will induce excess splicing losses (over 0.3 dB in practice) in the system. Finally residual whispering gallery modes (WGMs) still occur due to imperfections in the necessary absorbing layer [9], negatively affecting the bend loss spectrum over the range of measured wavelengths. Taken together these three disadvantages will have a detrimental effect on the performance and reliability of such a fiber bend loss edge filter.

In this paper the requirements for a fiber for a bend loss fiber based edge filter are described in detail. A generalized process of evaluation and selection for a suitable fiber, along with a design process for a bend loss fiber based edge filter is described. Our investigation includes: 1) a generalized methodology for the design of a fiber bend loss based edge filter; 2) an example of fiber evaluation; 3) determination of fiber bending radius and length for the fiber; 4) experimental verification for a sample fiber, where the sample fiber selected is SMF28e. The good agreement between theoretical modeling and measured results for the sample fiber confirms that the generic process proposed for fiber evaluation, selection and filter design is effective, resulting in improved baseline loss, discrimination range and PDL performance and ease of fabrication for the filter.

2. The process of bend loss based edge filter design

The design process for an edge filter involves a number of critical steps. Firstly the required spectral parameters of the edge filter must be decided; in particular the baseline loss and the discrimination range over the wavelength range of interest. Two key parameters for an edge filter are baseline loss and discrimination range. A bend-loss-based edge filter operates over a wavelength range from λ_1 to λ_2 with a progressively larger attenuation as the wavelength increases from λ_1 to λ_2. The baseline loss is defined as the loss of the filter at λ_1, while the discrimination range is the difference between the attenuation at λ_1 and λ_2.

A second step is the evaluation of different fibers as to their suitability for use in the edge filter and a decision needs to be taken as to whether the fiber coating(s) need to be stripped or not, prior to fabrication. Finally once a fiber is selected, the exact value of bend radius and fiber length required must be determined.

Modeling of fiber bend loss is a very important part of this process. Theoretical modeling for fiber bend loss has been investigated for over 30 years [11-14]. D. Marcuse first developed a bend loss model for an optical fiber with a core-infinite cladding cylindrical structure [11]. Since then, a series of theoretical models and corresponding experimental investigations on macrobending loss have been presented, which considered the impact of WGMs caused by the reflection of the radiated field at the interface between the fiber cladding and coating layer. Examples include those presented in [12, 13], but these models are specific to a fiber with a single coating layer. In selecting a fiber for an edge filter application, fibers with multiple-coatings will need to be evaluated, so a model that can deal with multiple coatings is needed. A theoretical model based on a weak perturbance of fundamental mode propagation constants which considered single and multi-coating layers has been presented [14], which demonstrates a high level of agreement between calculated and experimental results. Therefore the theoretical formulation presented in Ref. [14] is employed in this paper to analyze the macrobending loss of singlemode fiber in this paper.

With regard to the required spectral response parameters of the edge filter, in our previous publication on ratiometric wavelength measurements [5], it was shown that for higher slope values for the transmission response of the edge filters for a given measurable wavelength range, the output ratio *R*, diverged from the actual transmission response of the edge filters at the upper end of the wavelength range due to the limited Signal-to-Noise Ratio (SNR) of real optical sources, e.g. a tunable laser. In regard to the spectral parameter baseline loss, as well as the fiber bend loss there are inevitable transmission losses, splicing losses, and insertion losses in such a system and these losses increase the baseline loss as well, reducing the overall signal power available for Optical-to-Electrical (OE) conversion and thus degrading accuracy due to noise. Consequently, for a fiber bend loss based edge filter used in a wavelength measurement application, the desired baseline loss should be lower than 5 dB and the desired discrimination range should lie in the range 15-20 dB [5-7].

Evaluating different fiber candidates as to their suitability for use in an edge filter involves a number of issues. In the first instance in order to minimize the excess splicing loss in the system, the physical parameters of a proposed fiber, such as the fiber core size, should be close to those of standard singlemode fiber typically used for interconnection between optical units in optical fiber systems. The bend loss sensitivity of the fiber is also important as it is desirable to minimize the physical length of the fiber used in the edge filter for three reasons: firstly to reduce the physical space occupied by the filter and most importantly to improve long term reliability by reducing the total length of the fiber subjected to mechanical stress; secondly reducing the physical length of fiber will also reduce polarization dependent loss and finally if the fiber coating has to be stripped off to be replaced by an absorbing layer then a shorter fiber length makes this processing step considerably easier. As a benchmark for fiber length if possible the fiber bending length should be significantly shorter than the circa 1.5 m length (22 turns) reported earlier for a SMF28 fiber (a low bend loss sensitivity fiber) based edge filter in Ref. [7].

Selecting a fiber for use in filter is an iterative process but one starting point to determine a range of useable NA values as a guide to initial selection. One approach to this is to select a reasonable target radius and maximum number of turns, hence setting a maximum length and then use the model to plot the baseline loss and discrimination range for different NA values. Based on previous results a bend radius circa 10.5 mm is a good starting point and based on the need for a reasonable bend length, as outlined above an upper a bend length of 5 turns is selected. The corresponding modeled baseline loss (bend loss at 1500 nm, plotted by a solid line) and discrimination range (the difference of bend losses between 1600 and 1500 nm, plotted by a dashed dot line) as a function of NA is presented in Fig. 1. The desired fiber diameter is defined as 8.3 μm, for good compatibility with SMF28, and discrimination range is defined within the common optical communication and sensing widows, from 1500 nm to 1600 nm.

As an example consider SMF28 fiber, which has an NA of 0.1285. Using Fig. 1, one can see that given the low bend loss sensitivity of the fiber, the baseline loss is acceptably low < 2 dB but the discrimination range is circa 10 dB, outside the desirable range of 15-20 dB discussed earlier [5-7]. The only solution, verified in practice, for a SMF28 fiber would be to use longer bend lengths. As will become evident in the next section and as shown in Fig. 1, selecting a fiber with lower NA value will increase the discrimination range, for example for an NA value of 0.1226, the calculated baseline loss is 4.64 dB, and the modeled discrimination range is 18.206 dB.

Finally in selecting a fiber, it is also necessary to consider the coating(s) used on the fiber. In general, to suppress the generation of WGMs, coatings are stripped off the fiber used in a bend-loss based edge filter and replaced with an absorbing layer. However removal of the coating adds to the fabrication complexity and also makes the fiber filter more fragile. Thus in selecting a fiber, an ideal coating would be one which showed a strong absorption over the wavelength range of interest, removing the need to strip the fiber coating in the first place. The decision here is complicated by the fact that manufacturers rarely release sufficiently detailed data on the absorption characteristics and chemical composition of the fiber coatings used in their products. This means that is difficult to determine from fiber specifications alone whether or not a coating can be left in place or not. One reliable approach is to measure the bend loss versus bend radius characteristic for a sample of the fiber. This will reveal a characteristic signature that is strongly influenced by coating absorption. By comparing the characteristic of the bent fiber with the characteristic predicted by the model [14] for the same fiber with an infinite coating assumed, one can determine whether or not the coating is an efficient absorber and thus if it can be retained or not. An example of this approach is provided in the next section.

Finally it should be noted that in the design of a fiber edge filter, there are mechanical limits on the usable bend radius. In previous experiments, it was found that a bare fiber filter was too fragile and easily broken when the bend radius was less than 10 mm for a bare fiber. Thus to ensure the reliability and longevity of the fiber bend loss filter, the fiber bend radius used should be ≥ 10 mm. If it is possible to retain the coating, a lower bend radius down to 8 mm is possible.

3. An example of fiber evaluation: SMF28e fiber

In Section 2 a generalized, systematic design methodology for evaluating and selecting candidate fibers for use in an edge filter was outlined. In this section an example of the use of the methodology is provided, which results in the selection of Corning SMF28e fiber as a suitable candidate.

From Figure 1 presented in Section 2, one can see that the NA of a candidate fiber should be in the range of 0.1222~0.1231@1550 nm to satisfy the requirements of baseline loss and discrimination range for an edge filter. As a starting point to demonstrate the selection of a suitable fiber for the filter a number of commercial fibers have been considered. Singlemode fiber S460HP from Nufern Ltd. with an NA=0.1228 and SM600 from Fibercore Ltd. with an NA=0.123 both have suitable NA values. However the core diameters of S460HP and SM600 are 3.5 and 3.85 μm respectively, and are significantly less that of the common fiber used for fiber interconnection and will result in excessive splice loss thus increases the baseline loss of edge filter as discussed in Section 2.

An alternative is Corning SMF28e, which has a suitable NA value (NA=0.123, cited in Ref. [15]). This is a fiber type which offers several advantages over traditional SMF28 fiber, such as lower attenuation at the so-called “water-peak” wavelength, but offering splice compatibility with SMF28, which makes SMF28e a more suitable candidate for further consideration compared to the two other fibers types cited above.

For standard Corning SMF28e fiber, both the manufacturing tolerances and NA changes induced by bending stress have been investigated and discussed in Ref. [15]. The composition of the fiber cladding for SMF28e is pure silica glass and refractive index (RI) is 1.4440 at 1550nm, confirmed by Corning. Therefore this value of cladding RI is chosen for the theoretical bend loss modeling. Based on the quoted MFD (10.4 μm@1550nm) of SMF28e in the Corning official specifications, the RI of the fiber core is chosen as 1.4490 in this paper.

For commercial Corning SMF28e fiber, there is a jacket with a thickness of 327.5 μm adhering to the outer coating layer, resulting in an overall fiber diameter of 900 μm. In our previous experiments [5-10, 14], all the fiber bend loss edge filters were coated with an absorbing layer, which eliminated wave-like WGM induced variations in the bend loss spectrum. Such wave-like variations are largely caused by WGMs formed at the interface between the outer coating layer and air (such as SMF28 [14]), or the interface of between the cladding and air where the coatings are stripped (such as 1060XP [9]). Ideally, if the jacket could completely absorb radiation, the bending SMF28e fiber could be treated as a fiber with core-cladding-infinite coating structure and practically there would be no need to strip the fiber jacket and apply an absorption layer, considerably simplifying the fabrication process.

As mentioned in Section 2, the manufacturer of SMF28e does not release detailed data about the jacket that would allow one to determine if the jacket absorbs radiation and suppresses the formation of strong WGMs at the coating-air interface. Thus to determine whether the jacket needs to be stripped or not, the bend loss of SMF28e fiber with a jacket was measured for bending radii over a range from 8 to 12 mm at the operating wavelength of 1550 nm. The measured results are compared to the results from a model, based on the theoretical formulas presented in Ref. [14] and also shown in the Fig. 2, which assumes an infinite coating, effectively a 100% efficient absorber. Based on the good agreement between the modeled and the experimental results, one can conclude that the jacket for SMF28e is acting as an efficient absorbing layer. Note that all bend radii take into account the radius of the fiber with a jacket (450 μm).

The theoretical modeling (solid line in Fig.2), utilizes a correction factor of 1.338 at 1550 nm, higher than a common conventional singlemode correction factor of 1.27 at a wavelength of 1300 or 1150 nm [12, 16]. The good agreement between measured and modeled values indicates that the so-called correction factor (effective bending radius) is required in modeling SMF28e fiber. As the correction factor varies slightly with wavelength in principle the correction factor needs to be determined for all wavelengths. However in practice it is acceptable to determine the correction factor at 10 nm intervals over the wavelength range of interest between 1500 and 1600 nm. For completeness the correction factors as a function of wavelength are shown in Fig. 3.

In summary the evaluation of SMF28e fiber so far shows that it is a potential candidate for use in an edge filter as it has a low splicing loss to conventional fibers and most importantly the fiber jacket is an efficient absorber, so that stripping of the jacket will not be needed in fabricating an edge filter.

4. Determination of fiber bending radius and length for an SMF28e based edge filter

A generic design methodology for macrobending fiber base edge filter has been presented in Section 2 and to verify the effectiveness of this methodology, a Corning SMF28e fiber has been selected using the methodology. The subsequent design of the macrobending fiber filter based on SMF28e has been presented in Section 3 and involves determining the bending radius and bending length to provide a desired baseline loss and discrimination range for the edge filter, In this section we present an evaluation of the designed SMF28e fiber based edge filter, including consideration of the polarization sensitivity of the bend loss over the range of measured wavelengths.

Fig. 4 shows the calculated baseline loss per turn at a wavelength of 1500 nm and discrimination range per turn as a function of different bending radii, where the fiber bending length is one turn. From the Fig. 4, one can see that as the bend radius increases, the non-monotonic decrease of both the baseline loss and discrimination range as a function of bend radius confirms the presence of a residual WGM effect at the interface between the cladding and the coating layers.

In the first instance from Fig 4, and Table 1 it is clear that there are multiple solutions of bending radius and bending length for the fiber edge filter. For a given bend radius a useful approach is to divide the minimum discrimination range target of 15 dB by the discrimination range value in dB/turn from Fig. 4. If the number of turns is acceptable, typically a single digit value, then one can proceed to check the baseline loss by multiplying the number of turns by the baseline loss value in dB/turn. If this is less than 5 dB then such a filter is feasible. Using this approach and to help interpret Fig 1, some baseline loss and discrimination values for selected bend radii are shown in Table 1, along with the minimum number of turns needed to reach a target discrimination range of 15 dB and the resultant baseline loss.

It can be seen from Table 1 that filters with bend radii of 8.45 and 9.45 mm would need 6.5 and 5.7 turns of fiber respectively to reach the minimum discrimination range of 15 dB but that such filters would breach the 5 dB limit for baseline loss. A bend radius of 12.95 mm is not usable for a different reason, the low discrimination range value in dB/turn would mean that to achieve 15 dB of discrimination would require about 110 turns of fiber, a very long length of fiber that is likely to result in a very high PDL value. It is also clear from Table 1 that using bend radii of 8.95, 10.95 and 11.45 mm would all produce a filter with an acceptable number of turns and a baseline loss less than 5 dB.

These three candidate designs are chosen with bend radii of 8.95, 10.95 and 11.45 mm and a multiple turn structure. The number of turns in each case is adjusted upwards from the value in Table 1 to round off the number of turns to an integer value for ease of fabrication and also to provide discrimination ranges that are distributed over the range of 15-20 dB. Along with the bend radius and number of turns, the calculated baseline loss and discrimination range are summarized in Table 2 for each of the three filters.

In Ref. [8], it is shown that the fiber polymer coating layer has a significant influence on the bending induced PDL, and that higher PDL values will reduce the accuracy of wavelength measurement. The corresponding PDLs for the three candidate designs in Table 2 are calculated based on scalar approximation method by using the technique presented in [8]. The theoretical polarization dependent losses for the three different bending radii and bending lengths are shown in Fig. 5. The calculated PDL results were determined with correction factors applied at 10 nm intervals, over the wavelength range of interest between 1500 and 1600 nm. From Fig. 5, one can see that the maximum PDL value (0.475 dB at 1600 nm) occurs with a bending radius of 11.45 mm, clearly larger than the maximum PDLs for bending radii of 8.95 (solid line) and 10.45 mm (dashed dot line). Therefore for experimental verification of the candidate designs, two of the designs in Table 2 were chosen, that has bending radii of 8.95 and 10.95 mm. This selection process underscores the need to include an estimate of likely PDL in the design of an edge filter.

5. Experimental verification and discussion

Using a tunable laser and an optical spectrum analyzer, the bend loss was measured as a function of wavelength between 1500 and 1600 nm for the two SMF28e fiber based edge filters selected in the last section. The theoretical and experimental macrobending losses over the wavelength range from 1500 to 1600 nm for edge filters with a bend radius of 8.95 (bend length of 2 turns) and 10.95 mm (bend length of 9 turns) are presented in Fig. 6. From Fig. 6, one can see that there is reasonable overall agreement between the calculated modeling and experimental data. For example for a bend radius of 10.95 mm the measured baseline transmission loss is about 5.096 dB at the wavelength of 1500 nm (calculated value is 4.82 dB) and the measured discrimination range is circa 17.418 dB from 1500 to 1600 nm (calculated value is 16.97 dB) . The discrepancies between the calculated and measured results are most likely a result of: 1) the approximations made in the calculation, 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 explained in Ref. [12-14]; 2) the application of a correction factor at only a limited number of wavelength points (10 nm intervals) in the calculation of bend loss and 3) the experimental accuracy of the bend radius (both baseline loss and discrimination range are sensitive to the bend radius as presented in

Fig. 4,

One final reason for the deviations between calculated and measured results in Fig. 6, are the residual wave-like variations in the transmission spectrum over the wavelength range from 1580 to 1600 nm, in particular for a bending radius of 8.95 mm. The main source of such variations is the formation of WGMs at the interface of the cladding and coating. In practice, from Fig. 4, one can see that the wave-like variations were more evident when the fiber bending radius was smaller than 9.45 mm in the SMF28e fiber bend loss measurements, as a result of stronger WGMs at lower bend radii.

Finally, we experimentally investigated the PDL performances of bending SMF28e fiber over the range from 1500 to 1600 nm at the bend radius of 8.95 (bend length of 2 turns) and 10.95 mm (bend length of 9 turns). The measured average PDL results are 0.0312 dB for the case of bend radius of 8.95 dB, and 0.0871 dB for the case of bend radius of 10.95 mm, significantly better than 0.1072dB of SMF28 fiber and 0.0922dB of 1060XP fiber presented in Ref. [9].

6. Conclusion

In this paper, a generalized methodology for the design of a fiber bend loss based edge filter has been investigated and presented, starting with the task of selecting suitable fibers and then considering the design of the fiber bending loss edge filter. To evaluate the proposed generic design methodology, a Corning SMF28e fiber with a jacket is selected and sample filters using this fiber are designed and two are selected for experimental verification. There is good agreement between theoretical modeling and measured results for the sample fiber. The edge filters deigned meet target specifications for baseline loss and discrimination range and show a lower average PDL than previous reports. The filters are also compact and are easy to fabricate. The buffer jacket can be retained on the fiber, reducing fiber stress and thus improving long term reliability. Overall these results confirm the effectiveness of the generic process discussed and proposed in this paper for fiber evaluation, selection and edge filter design.

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Figure Captions:

Fig. 1 Calculated baseline loss and discrimination range as a function of different fiber NA with a fiber length of 5 turns when the bend radius is 10.5 mm.

Fig. 2 Theoretical modeling with correction factor and experimental bend loss results for SMF28e fiber for different bending radii at a wavelength of 1550 nm and 10 turns of fiber.

Fig. 3 Correction factor as a function of wavelength for SMF28e fiber.

Fig. 4 Calculated baseline loss (bend loss at the wavelength of 1500 nm with the correction factor of 1.335) and discrimination range versus different bending radii; the fiber length is one turn.

Fig. 5 Calculated polarization dependent losses of SMF28e fiber with the bending radius of 8.95 (solid line), 10.95 (dashed dot line) and 11.45 mm (dashed line), and with the lengths of 2 turns, 9 turns and 10 turns, respectively.

Fig. 6 Calculated (solid symbols connected with solid lines) and measured (* and + symbols) macrobending results for bend SMF28e fiber at the bend radius of 8.95 and 10.95mm, respectively.

Table Captions:

Table 1 Calculated parameters versus bending radii for selected bend radii with a target discrimination range of 15 dB.

Table 2 Calculated baseline loss and discrimination range versus selected bending radii with different fiber length

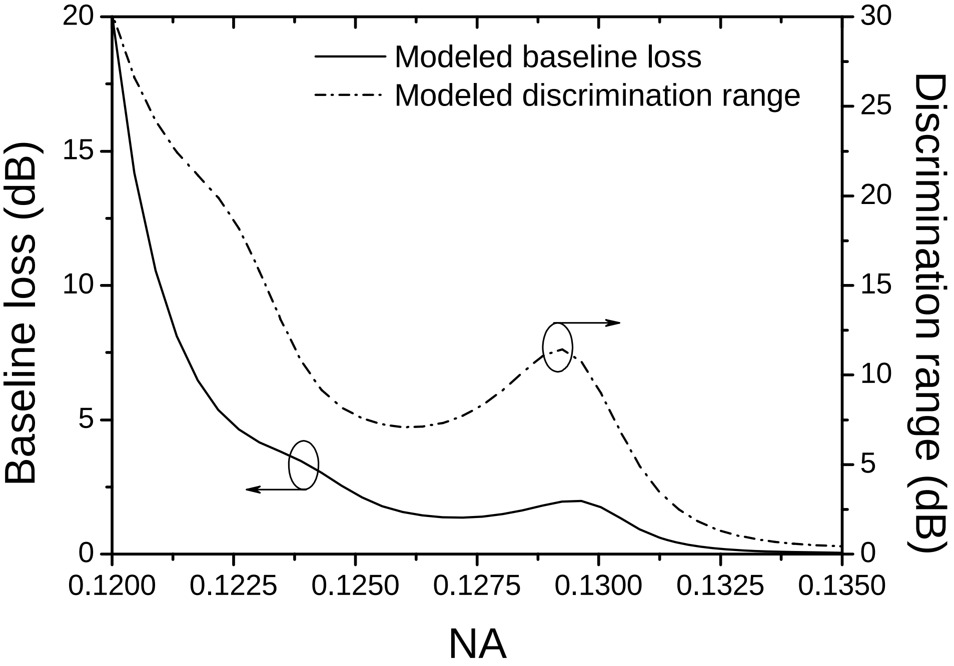
Modeled baseline loss
Modeled discrimination range
Baseline loss (dB)
Discrimination range (dB)
NA
0
5
10
15
20
0
5
10
15
20
25
30
0.1200
0.1225
0.1250
0.1275
0.1300
0.1325
0.1350

Fig. 1

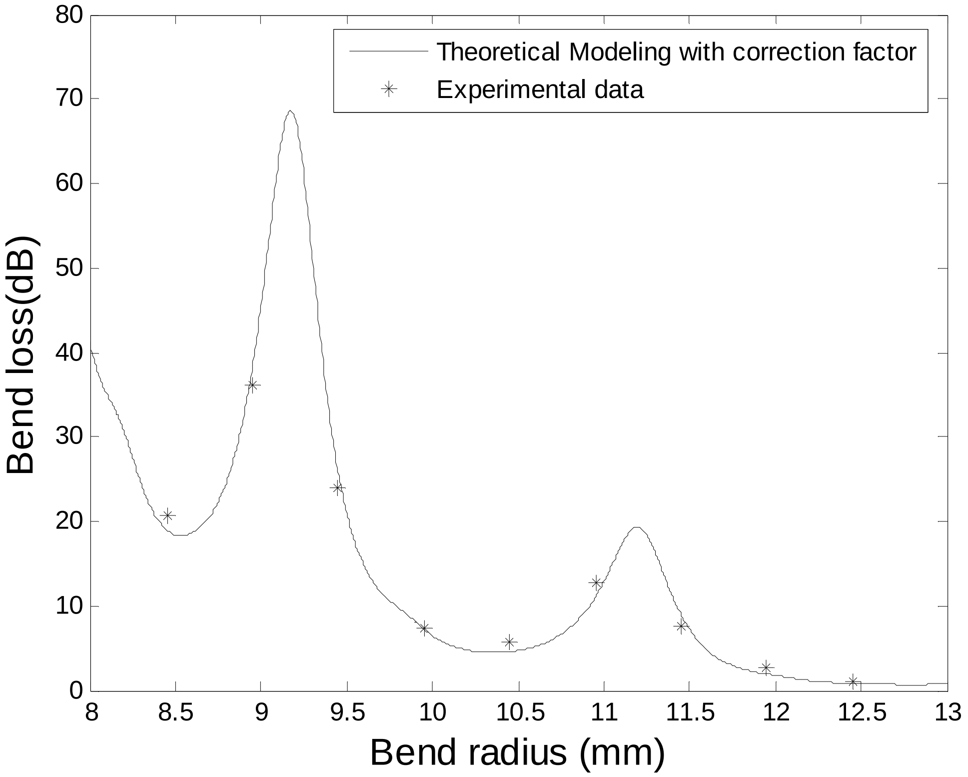
Theoretical Modeling with correction factor
Experimental data
Bend loss(dB)
Bend radius (mm)
0
10
20
30
40
50
60
70
80
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
13

Fig. 2

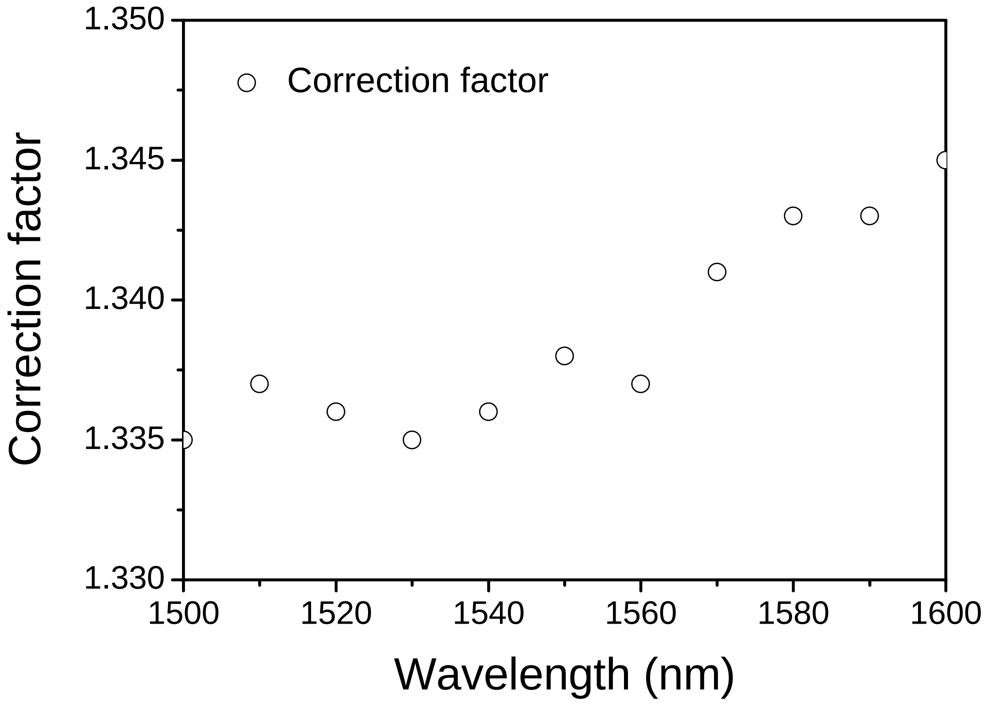
Correction factor
Correction factor
1.350
1.345
1.340
1.335
1.330
1500
1520
1540
1560
1580
1600
Wavelength (nm)

Fig. 3

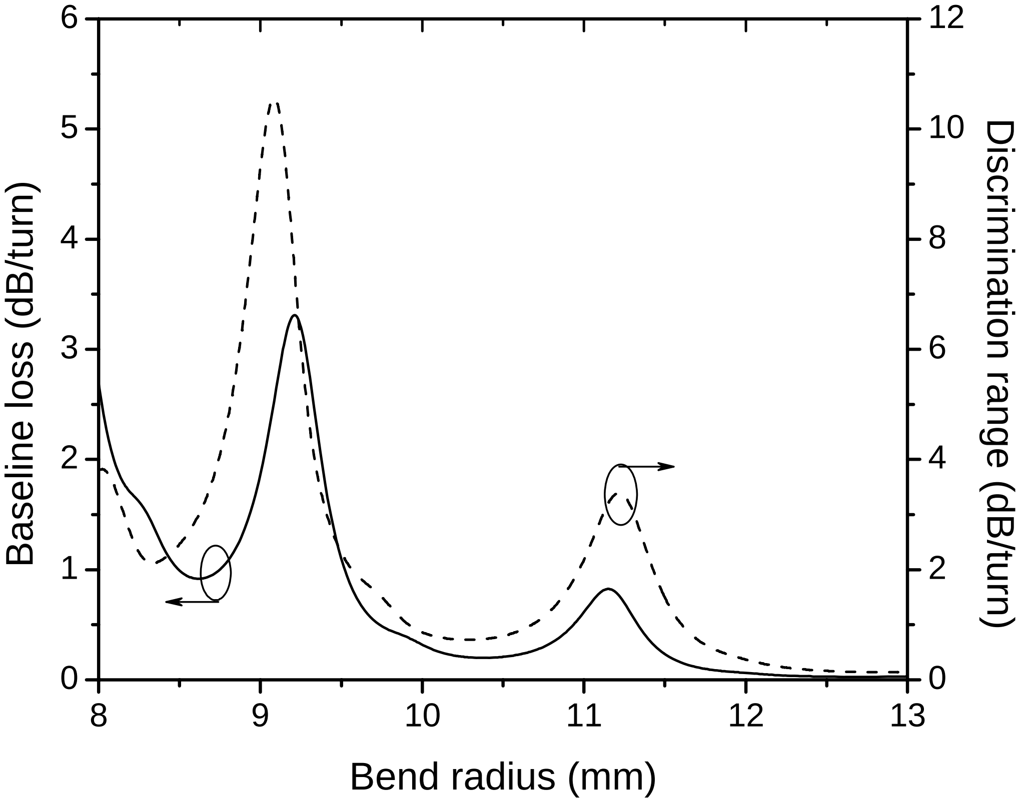
0
1
2
3
4
5
6
Baseline loss (dB/turn)
0
2
4
6
8
10
12
Discrimination range (dB/turn)
8
9
10
11
12
13
Bend radius (mm)

Fig. 4

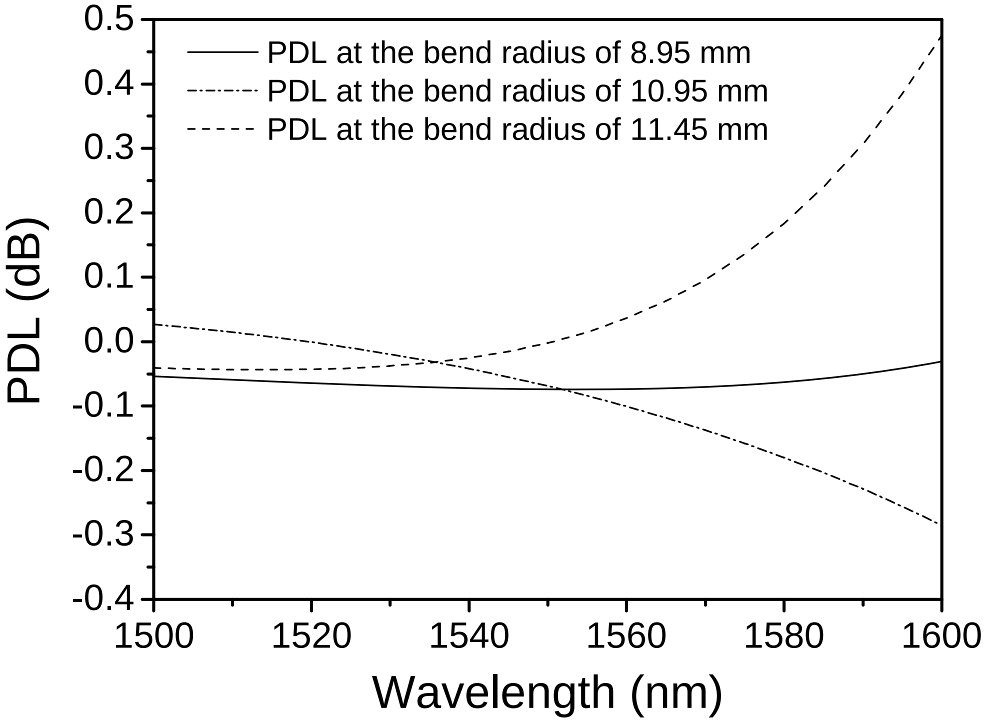
PDL at the bend radius of 8.95 mm
PDL at the bend radius of 10.95 mm
PDL at the bend radius of 11.45 mm
PDL (dB)
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
1500
1520
1540
1560
1580
1600
Wavelength (nm)

Fig. 5

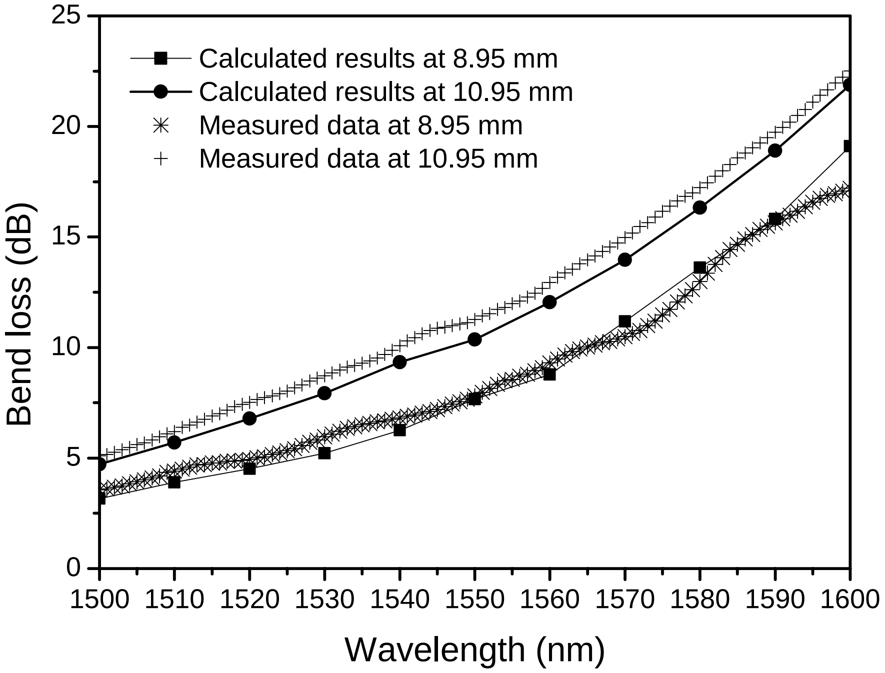
Calculated results at 8.95 mm
Calculated results at 10.95 mm
Measured data at 8.95 mm
Measured data at 10.95 mm
Bend loss (dB)
Wavelength (nm)
0
5
10
15
20
25
1500
1510
1520
1530
1540
1550
1560
1570
1580
1590
1600

Fig. 6

Table 1 Calculated parameters versus bending radii for selected bend radii

Bend radius (mm)	**Baseline loss (dB/turn)**	**Discrimination range (dB/turn)**	**Min number of turns**	**Total Baseline loss (dB)**
8.45	1.08	2.31	6.5	6.98
8.95	1.58	7.98	1.9	2.97
9.45	1.39	2.64	5.7	7.90
10.95	0.52	1.89	8.0	4.17
11.45	0.29	1.83	8.2	2.39
12.45	0.03	0.17	88.6	2.65
12.95	0.03	0.14	110.4	3.31

Table 2 Calculated baseline loss and discrimination range versus selected bending radii with different fiber length

Selected Bend radius (mm)	**Fiber bending length(turns)**	**Baseline loss (dB)**	**Discrimination range (dB)**
8.95	2	3.16	15.96
10.95	9	4.72	16.97
11.45	10	2.91	18.27