Near zero bending loss in a double-trenched bend insensitive optical fiber at 1550 nm

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Abstract: We have developed a new single-mode optical fiber (SMF) which exhibits ultra low bend sensitivity over a wide communication band. The measured mean bending loss at 1550 nm was about 0.0095 dB for a loop of 10 mm diameter.

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1. Introduction

Increasing growth of FTTH applications in the optical fiber communication has caused various research groups and companies to come forward with innovative products that meet the stringent requirement of FTTH applications [1–7]. Due to sharp bends in FTTH type optical communication system, the conventional single-mode fibers (SMF, G.652.D) that use the uplink and the downlink with 1.31 µm and 1.55 µm wavelength, respectively, have been replaced by bend insensitive optical fibers (BIF) having very low bending loss. The ITU-T standard for the single mode optical fiber (SMF) has been categorized under G652.D where mode field diameter (MFD) has to be about 8.6-9.5 µm at 1310 nm and the zero dispersion wavelength should be about 1300-1324 nm that means the MFD should be at least 9 µm at 1550 nm and the dispersion should not be larger than 18.5 ps/km.nm at 1550 nm [2]. The bend insensitive optical fiber has been standardized under the G.657 standard describing two fiber categories: (a) Class A has tightly specified fiber properties with practical macrobend loss requirements, for example, maximum bending loss at 15 mm of bending diameter should...
be less than 1 dB/loop at 1550 nm, and (b) Class B has very stringent bend loss requirements, for example, maximum bending loss at 15 mm of bending diameter should be less than 0.5 dB/loop at 1550 nm. Additionally, the optical fiber under G.657.A should follow the G652.D norms, while the specifications of G.657.B are liberal to support all existing unique and non-standard bend insensitive fibers. There are several reported optical fibers that meet and exceed the requirements of G.657.A and exceeds the bending loss requirement of G657.B, making them the best choice for networks requiring bend optimized performance [3,4]. Apart from this, theoretical designs to optimize the bend insensitivity of BIF have been addressed in [8,9]. For a quick review, some of the existing bend insensitive optical fibers are listed in Table 1. The G657.B/G652.D compatible optical fiber having nano-engineered holes around the core has the bending loss of 0.03 dB/loop at 1550 nm for the bending diameter of 10 mm, but it did not comply fully with G652.D [5]. One more BIF with extremely low bending loss of about 0.02 dB/loop has been reported having the MFD of around 6.7 µm at 1550 nm (6.3 µm at 1310 nm) [6]. According to a recently published report, combination of the MFD and the trench optimization has resulted in the bending loss of just 0.014 dB at 1550 nm for a loop of 10 mm diameter, where the optical fiber was compatible with the G657.A and G527.B ITU-T requirements, but MFD was not strictly according to the G652.D requirements [10].

A quick survey of Table 1 indicates that, in a quest to have a near zero bending loss value (below 0.03 dB/loop) and still to comply with the ITUT G652.D + G652.A/B recommendations, one has to settle for costly and not-so-easy to fabricate nano-engineered fibers. A great challenge is then to make available a low-cost and easy to fabricate BIF that fully follows the ITUT G652.D and G652.A/B recommendations. To achieve such an ultra low bending loss, what needed is the enhancement of depressed-index trench, which is usually made by doping boron oxide (i.e., di-boron tri-oxide) in the silica cladding. As a typical case, for the optical fiber with cutoff wavelength of 1220 nm, the effect of increasing trench width is shown in Fig. 1, where it can be found that the bending loss can be decreased with

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<tbody>
<tr>
<td>SMF [1]</td>
<td>57.17</td>
<td>16.6</td>
<td>9.9 (9.2)*</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Single trenched BIF [3]</td>
<td>0.05</td>
<td>~17</td>
<td>9.6 (8.7)*</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Holey trenched BIF [4]</td>
<td>0.03</td>
<td>~18</td>
<td>9.7 (8.7)*</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>BIF [5] untrenched</td>
<td>1.17</td>
<td>11.84</td>
<td>7.5 (~7)*</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>BIF [6] Ultra Trenched</td>
<td>~0.02</td>
<td>&lt;= 18</td>
<td>6.7 (6.3)*</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>BIF [10] Trenched</td>
<td>0.014</td>
<td>~18</td>
<td>7.7 (7.4)*</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
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</table>

* MFD at 1310 nm, ** φ is the loop diameter
increasing the trench width. A pitfall of reducing the bending loss by adopting this method is that the optical fiber preform suffers a mismatch of thermal expansion coefficients of the boron oxide doped (trench) and undoped silica glass layers, which usually results in the formation of cracks while drawing the fiber from this preform.

Thus, manufacturing the ultra low bending loss optical fiber using the depressed-index trench is experimentally very challenging: (a) How to achieve a successful fabrication of a wide depressed-index trench? (b) How to reduce the bending loss than that of the existing BIFs? During the several experiments, we found that cracking in the depressed-index trench preform can be controlled by adopting a segmented deposition of boron oxide instead of a single wide layer. Therefore, we adopted the solution of segmented low-index trench. The next query can be about the number of trenches to be used. To answer this query, we have to note that it will be a tremendous experimental task to optimize the trench width of multiple trenches and silica layers that separate them due to the diffusion of boron ions into surrounding layers. Therefore, from the experimental point of view, it is best to use a minimum number of trenches, and as only one wide trench was out of question due to experimental difficulties discussed earlier, we decided to use two trenches in the BIF. Then next query is: can two trenches really reduce the bending loss similar to the wide single trench? To address this issue theoretically, we chose the single trenched and the double trenched optical fiber as shown in the inset of Fig. 2. Total widths of trenches in both fibers are the same. The bending loss performance of the double trenched optical fiber was found to be similar or somewhat better than the single trenched optical fiber as shown in Fig. 2. Similarly, if we consider another optical fiber with 1220 nm cutoff wavelength, a double depressed-index cladding structure with the trench refractive index of 1.44 at 1550 nm, the bending loss similar to a wide single trenched optical fiber can be obtained (as shown in Fig. 1 and Fig. 3); a separation between two depressed-index trenches can also be used potentially to reduce the bending loss as shown in Fig. 4.
Fig. 2. Theoretical bending loss in the single trench and the double trench optical fiber. Single trench was 10 µm wide while in the double trenched fiber, each trench was 5 µm wide with 5 µm separation. Their bending loss performance can be seen to be similar.

Fig. 3. Effect of trench width on the bending loss of double-trenched optical fiber. When one trench width was varied, other trench width was held constant at 3.55 µm.
To calculate results of Fig. 1 to Fig. 4, we used the commercial FiberCAD code [11] to solve propagation equations and to calculate the bending loss of double-trenched fiber. The macro-bending loss in the units of dB/km was calculated by using [11–13]:

\[
\alpha_{macro} = \frac{10}{\log_{10} 10} \left( \frac{\pi V^8}{16 a R_w^2} \right)^{1/2} \exp \left( -4 R_b \Delta W^3 \right) \frac{\int_0^\infty (1 - g) F_0 r dr}{\int_0^\infty F_0^2 r^2 dr} \quad (1)
\]

where \( F_0 \) is the radial field of fundamental mode, \( a \) denotes the fiber core radius in meter, \( R_b \) is the bend radius in meter, \( n_{max} \) and \( n_{min} \) are the maximum and minimum values of refractive index and other parameters appearing in above equation are given by:

\[
g = \frac{n(r)^2 - n_{min}^2}{n_{max}^2 - n_{min}^2}; V = k_0 a \sqrt{n_{max}^2 - n_{min}^2} ;
\]

\[
W = a \sqrt{\beta^2 - (k_0 n_{min})^2}; \Delta = \frac{n_{max}^2 - n_{min}^2}{2n_{max}^2} \quad (2)
\]

The bending loss calculated using Eq. (1) can be converted to units of dB/loop using the relationship:

\[
\alpha_{macro} \text{ (dB/loop)} = 0.00628 \times [\alpha_{macro} \text{ (dB/km)}] \times R_b \quad (3)
\]

2. Experiments

We used the modified chemical vapour deposition (MCVD) technique to fabricate the optical fiber. The core of optical fiber preform was formed by depositing about 3.65 molar\% of GeO\(_2\) in silica at 2000 °C. After depositing several silica layers around the core (to avoid effects of the trench on dispersion properties of fiber), a depressed-index trench surrounding the core was formed by depositing about 10 molar\% of B\(_2\)O\(_3\) in silica. This was followed by second
deposition of silica layers that was further followed by the second depressed-index trench with about 6.5 molar% of B$_2$O$_3$ in silica. Thus, two trenches had silica layers acting as the separation between them. The preform was slowly cooled down stepwise from 2300 °C to the room temperature to relax residual stresses because suddenly stopping the burner at 2300 °C can crack the deposited part of preform. To separate preform from the supporting tube, we used an oxy-hydrogen flame rather than using any mechanical saw. The preform was then loaded at the drawing tower where it was slowly heated from 25 °C to 2000 °C. The optical fiber with outer diameter of 125 µm was drawn from this preform at 2000 °C. The refractive index profile of the optical fiber was measured by using the NetTest P104 preform analyzer and it is illustrated in Fig. 5 where two distinct depressed-index trenches separated by silica layers can be observed. A central index dip as shown in Fig. 5 is typical characteristics of the preform made by using the MCVD process and occurs due to evaporation of germanium monoxide at a high temperature of 2300 °C while sealing the tube. Optical parameters of the double-trenched BIF are listed in Table 2. It can be mentioned that authors had earlier proposed optimized design parameters for the double-trenched optical fiber to have an ultra low bending loss of about 0.002 dB/loop at 1550 nm for 10 mm of the bending diameter [8]. However, while experimentally fabricating the optical fiber, due to laboratory constraints, it was difficult to strictly follow theoretical parameters because of a required precise boron-doping calibration. We chose to overfill trench requirements and the result was an ultra low bending loss of about 0.0095 dB/loop (as discussed ahead), which fell short of theoretical expectations [8].

![Fig. 5. Refractive index profile of the double-trench optical fiber fabricated using the MCVD process.](image)

### Table 2. Optical parameters of the double-trenched single mode optical fiber fabricated using the MCVD technique.

<table>
<thead>
<tr>
<th>$\Delta n_1$</th>
<th>$\Delta n_2$</th>
<th>$\Delta n_2$</th>
<th>$2a$ (µm)</th>
<th>$b$ (µm)</th>
<th>$c$ (µm)</th>
<th>$d$ (µm)</th>
<th>$e$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer trench</td>
<td>Inner trench</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0055</td>
<td>−0.0046</td>
<td>−0.005</td>
<td>8.9</td>
<td>6.75</td>
<td>7.1</td>
<td>4.6</td>
<td>5.7</td>
</tr>
</tbody>
</table>

The fiber had the LP$_{11}$ cutoff wavelength of 1192 nm and it was estimated by measuring the bending loss after using several tens of bending loops at low bending diameter; a few turns cannot produce the measurable loss to estimate the cutoff point. We used a low power (~60 dBm) broadband light source as the input source. A typical curve that was used to estimate the
Cutoff wavelength is shown in Fig. 6, which shows that the experimental cutoff wavelength for the BIF was 1192 nm. To measure the bending loss, we spliced two single-mode fibers at two ends of the BIF and the optical power was measured by using the optical power meter and its spectral variation was measured using the spectrum analyzer. An amplified spontaneous emission light source (ASE source, Thorlabs ASE730, 12 dBm) emitting at C/L band was used as the input source. The bending loss was measured at different loops of 10 mm bending diameter.

![Fig. 6. Determination of cutoff wavelength of the double-trenched optical fiber.](image)

3. Results and discussion

Typical transmission spectra of the straight fiber before and after bending along with spectral variations of the bending loss of our BIF are illustrated in Fig. 7, where it is seen that the bending loss was almost negligible for the wavelength band of 1500 nm to 1600 nm at the bending diameter of 10 mm. For a very small loop of 4.5 mm diameter, the loss was limited to 0.7-1.5 dB/loop in the entire band of 1500-1600 nm; however, one has to take a risk breaking fiber by making such a small loop. To estimate the bending loss, we used several bending loops and measured the bending loss at different benches; variations of the bending loss with respect to the number of loops are shown in Fig. 8. It can be found from Fig. 8 that measurements were fairly similar at different benches and the mean bending loss at 1550 nm was about 0.0095 dB for one loop of 10 mm diameter. Similarly, variations of the bending loss at different loop numbers are shown in Fig. 9 for the 4.5 mm of bending diameter and the mean bending loss was about 0.946 dB at 1550 nm for one loop of 4.5 mm diameter. Reason for such a low bending loss can be described as follows: when an optical fiber is bent, the fiber becomes a leaky structure causing the power in the core to leak into the cladding. At the bend, the effective refractive index of cladding becomes larger than the effective index of core to leak a large amount of power in the cladding into the surrounding rather than couple back into the core after the bend is over, causing the bending loss and it can be avoided if its effective index at bend is made smaller than the core effective index. In our BIF, this was done by adding depressed-index layers in the cladding structure. Typical photographs comparing the bending loss in the cabled single mode optical fiber and the double trenched BIF when their loops were held by fingers are shown in Fig. 10 and Fig. 11.
Fig. 7. Transmission spectra and spectral variations of the bending loss of double-trenched optical fiber at 4.5 mm and 10 mm of bending diameters.

Fig. 8. Measured bending loss of the double-trenched optical fiber at 1550 nm for different number of loops with 10 mm of bending diameter. Dashed lines are guide to the eye.
Fig. 9. Measured bending loss of the double-trenched optical fiber at 1550 nm for different number of loops with 4.5 mm of bending diameter. Dashed lines are guide to the eye.

Fig. 10. Photographs showing the bending loss in the commercial jacketed single mode optical fiber at 1550 nm upon 10 mm of bending diameter: (a) when the fiber was straight, and (b) when it was bended. The bending loss was 6.01 dB/loop as shown by the power meter.

Fig. 11. Photographs showing the bending loss in the double trenched BIF at 1550 nm upon 10 mm of bending diameter: (c) when the fiber was straight, and (d) when it was bended. The bending loss was negligible.

Very important next thing for any BIF is its ability to integrate in the existing optical fiber network that is made of single mode optical fibers. We tested the splicing of our double trenched BIF with the commercial single mode optical fiber [14], and it was found that the
fusion splicing SMF and BIF was a simple issue requiring no special skills. A typical photograph illustrating fusion splicing between the SMF and the BIF is shown in Fig. 12.

![Fig. 12. A measurement showing the fusion splice between the single mode optical fiber (left) and the BIF (right).](image)

Splice losses in terms of the transverse offset and the longitudinal offset were measured between the single mode optical fiber and the BIF at 1550 nm. To measure the transverse offset loss, two fibers were separated by 5 \( \mu \)m of distance and the SMF was moved up or down in a plane parallel to the end-face of optical fiber. A perfectly aligned axis between two fibers was considered as the reference point and all losses were recorded with reference to this point as shown in Fig. 13.

![Fig. 13. The transverse offset loss between the single mode fiber and the bend insensitive fiber at 1550 nm. Two fibers were held apart by a distance of 5 \( \mu \)m.](image)

Similarly, the longitudinal offset loss between the single mode fiber and the bend insensitive fiber was measured by initially keeping two fibers a 5 \( \mu \)m apart and then moving the single mode fiber perpendicular to the plane containing the end-face of optical fiber. Measured longitudinal offset loss variation is illustrated in Fig. 14.
Fig. 14. The longitudinal offset loss between the single mode fiber and the bend insensitive fiber at 1550 nm. The loss was calculated relative to the loss at 5 µm of separation.

All optical parameters of the double-trenched BIF are listed in Table 3, which are quite comparable with the ITU-T G.567.A and G.567.B recommendations of the single mode fiber. In Table 3, bending loss values were obtained experimentally while the dispersion and MFD characteristics were obtained by using the FiberCAD code. Typical dispersion and MFD characteristics of the double-trenched optical fiber are shown in Fig. 15, where it can be observed that the MFD is 10.4 µm at 1550 nm and the dispersion is about 18.5 ps/km.nm at 1550 nm.

Table 3. Optical parameters of the double-trenched single mode optical fiber at 1550 nm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion* at 1550 nm (ps/km.nm)</td>
<td>18.5</td>
</tr>
<tr>
<td>Zero dispersion wavelength* (nm)</td>
<td>1301</td>
</tr>
<tr>
<td>Dispersion slope* (ps/(km.nm)^2)</td>
<td>0.085</td>
</tr>
<tr>
<td>MFD* (µm)</td>
<td>10.4</td>
</tr>
<tr>
<td>Bending loss** (dB/loop)</td>
<td>0.0095</td>
</tr>
<tr>
<td>Bending loss** (dB/loop) φ = 4.5 mm</td>
<td>0.946</td>
</tr>
</tbody>
</table>

φ = Bending loop diameter, *Theoretical, **Measured (**Bending loss < 0.01 dB at φ = 15 mm, 25 loops)
4. Summary

We have developed the double trenched optical fiber as the bend insensitive optical fiber for FTTH application. The measured bending loss was about 0.0095 dB/loop and 0.946 dB/loop at 10 mm and 4.5 mm of bending radius, respectively and its optical properties approximately followed the ITU-T G.652.D, G.657.A and G657.B recommendations.

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