Recent Developments of Bend-insensitive and Ultra-bend-insensitive Fibers

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Abstract
In this paper, we address our most recent works on all-solid bend-insensitive fibers (BIFs) and Ultra BIFs (UBIFs) made with the versatile PCVD process. The influence of connection losses on Multi-Path Interference (MPI) phenomenon is analyzed in these fibers. Notably, we demonstrate that compliance with G.652 specifications in term of cable cutoff wavelength ensures a very high tolerance to MPI in Fiber-To-The-Home networks. Then, we address the spliceability of such fibers using fusion and mechanical splicing. Reported statistics demonstrate excellent splicing performance for BIFs and UBIFs as well as an excellent backward compatibility with G.652 standard single-mode fiber. Finally, we illustrate the robustness of the all-solid single-trench-assisted concept by showing how simple controls of the PCVD process allows to tightly limit the distributions of fiber characteristics, especially the cable-cutoff-wavelength and of the macro-bend-loss distributions.

Keywords: Single Mode Fibers; Bend Insensitive Fibers; ITU-T Recommendation G.657; Bend Losses; FTTH.

1. Introduction
The emergence of Fiber-To-The-Home (FTTH) networks subject to harsher environments than Long-Haul (LH) networks has spurred the development of bend-insensitive fibers (BIFs) compliant with both G.657.B (see Table. 1) and G.652.D ITU-T recommendations. These fibers have profiles with standard central cores assisted by depressed index areas in the cladding (solid single trench [1-4], solid multiple trenches [5], air-hole trench [6,7]).

Table 1. G.657.B ITU-T recommendation

<table>
<thead>
<tr>
<th>Attributes</th>
<th>G.657B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Cutoff Max.</td>
<td>1250 nm</td>
</tr>
<tr>
<td>MFD 1310nm Nominal range</td>
<td>6.3 - 9.5 µm</td>
</tr>
<tr>
<td>Tolerance</td>
<td>± 0.4 µm</td>
</tr>
<tr>
<td>Macrobending loss</td>
<td></td>
</tr>
<tr>
<td>Radius (mm)</td>
<td>15</td>
</tr>
<tr>
<td>Number of turns</td>
<td>10</td>
</tr>
<tr>
<td>Max. at 1550nm (dB)</td>
<td>0.03</td>
</tr>
<tr>
<td>Max. at 1625nm (dB)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Using a simple and robust all-solid single-trench-assisted profile, we developed as early as 2006 the first BIF [1,2] compliant with both G.657.B and G.652.D ITU-T recommendations. In 2008, we introduced a G.652.D Ultra-BIF (UBIF) [3,4] that exhibits bend losses 10 times lower than G.657.B and <0.10dB/turn at 5mm bend radius at 1550nm. This fiber is a good candidate for component intra-connection and specialty applications.

In this paper, we address our most recent works on these two fiber types. In section 2, we present our investigations on the Multi-Path Interference (MPI) phenomenon that has recently been identified as a new concern in FTTH deployments [3,8,9]. We will particularly focus on the impact of splices/connections losses on MPI and show that acceptable MPI levels can be obtained even in extremely degraded cases (>1dB/splices). In section 3, we detail our work on the spliceability assessment of these fibers, and cover fusion and mechanical splices. In section 4, we illustrate the robustness of our all-solid single-trench-assisted concept by showing how simple control of the versatile PCVD process allows to tightly limit the distributions of our BIF and UBIF characteristics.

2. MPI Investigations
MPI is one important parameter that has rarely been addressed up to now. Known for a long time in LH networks, it is a well-known way to estimate the impact of a few-mode behavior when the system is operated lower or close to the cutoff wavelength. MPI is

Table 2. Typical characteristics of all-solid single-trench-assisted BIF and UBIF

<table>
<thead>
<tr>
<th>Sample</th>
<th>BIF</th>
<th>UBIF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Cutoff (nm)</td>
<td>1210</td>
<td>1230</td>
</tr>
<tr>
<td>MFD (µm) at 1310 nm</td>
<td>8.9</td>
<td>8.75</td>
</tr>
<tr>
<td>at 1550 nm</td>
<td>10.0</td>
<td>9.85</td>
</tr>
<tr>
<td>λ₀ (nm)</td>
<td>1318</td>
<td>1316</td>
</tr>
<tr>
<td>Slope at λ₀ (ps/nm²-km)</td>
<td>0.089</td>
<td>0.099</td>
</tr>
<tr>
<td>PMD (ps/km¡²)</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Loss (dB/km) at 1550 nm</td>
<td>0.190</td>
<td>0.188</td>
</tr>
<tr>
<td>at 1625 nm</td>
<td>0.201</td>
<td>0.199</td>
</tr>
<tr>
<td>Macro bending loss Wavelength (nm)</td>
<td>1550</td>
<td>1625</td>
</tr>
<tr>
<td>(dB/turn) 5 mm radius</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>7.5 mm radius</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>10 mm radius</td>
<td>0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>15 mm radius</td>
<td>0.001</td>
<td>0.005</td>
</tr>
</tbody>
</table>
more relevant to evaluate system impairments than just a cutoff characterization. In other words, a known MPI level relates to a power penalty. MPI received a renewed attention in the access network context due to the introduction of BIFs. In these new fibers, higher-order-mode mechanisms differ from those of a standard step-index Single-Mode Fiber (SMF). Thanks to MPI, we will be able to assess if the compliance with cutoff wavelength specified in G.652.D recommendations (i.e. cable cutoff wavelength $\leq 1260$nm) remains safe when working with BIFs or UBIFs.

Impact of stapling and incidental bends on MPI has already been studied $[3,8]$, showing no degradation in different FTTH deployment scenarios. In this section, we focus on the impact of splices/connections losses on MPI in single-trench-assisted BIF and UBIF developed with the PCVD process. Theoretical and experimental results are presented and discussed.

2.1 Characterization setup

MPI in FTTH networks differs from the one encountered in LH networks because the potential events causing it (splices, connections, staples, bends) are closely located on distance scales that become comparable to the laser coherent length. This coherent MPI exhibits a specific spectrum whose low frequency content is not accurately captured by high-pass filtering methods used in typical incoherent-based MPI situations such as in LH systems $[10]$.

Figure 1 details the experimental setup used to characterize the impact of fusion splices on coherent MPI. The splices between the fiber under test, 2m Single-Trench-Assisted Fiber (STAF) $[1-4]$ in our case, and the SMF pigtails are performed to cover 2 different scenarios:

- Normal conditions: splice losses are $<$0.1dB/splice at 1550nm (with 0.02-0.04dB typical values), the MPI performance are expected to be those encountered in the field. Here, the splicer does everything automatically, that is to say it aligns the fiber tips and forms the joint.

- Extreme conditions: splices are degraded to artificially exacerbate the MPI level. In semi-automatic mode, the splicer aligns the fibers before they get manually offset in one transversal direction to get $>$1dB/splice at 1550nm.

The MPI wavelength dependence is characterized every 5nm on a $\pm 1$nm window over the 1240-1350nm range. This procedure ensures that each measurement does not underestimate the MPI level and truly represents the worst possible case.

As coherent MPI level is not only related to fusion losses but also to cutoff-wavelength concepts, several fibers have been tested: fibers 1 & 2 are single-trench-assisted BIFs with cable cutoff wavelengths ($\lambda_{CC}$) of 1220nm (typical) and 1255nm (chosen to be close to 1260nm, i.e. the upper limit of G.652.D), respectively; and fiber 3 is a single-trench-assisted UBIF purposely chosen with a $\lambda_{CC}$ of 1250nm (whereas its typical value is 1230nm).

2.2 MPI Theory

The experimental setup is modeled as a Mach-Zehnder interferometer with 2 arms containing the $LP_{01}$ and $LP_{11}$ modes that propagate in the STAF sample. The splitters of this interferometer are positioned at the SMF-STAF connections. Solving the full-vectorial wave equation with a finite-element method to compute the modes properties and using an overlap-integral approach for the connection offsets, we calculate the $LP_{11}$ mode power excited at SMF-STAF connection, the $LP_{11}$ leakage loss along the STAF and the part of $LP_{11}$ signal that is re-coupled back into $LP_{01}$ mode at the STAF-SMF connection.

For same connection losses, the main parameter driving the MPI phenomenon is the $LP_{11}$ leakage loss, which can be different from fibers to fibers as shown in Figure 2. What is noticeable is that the $LP_{11}$ leakage loss of fiber 3 has a weaker dependence with wavelength than that of fibers 1 or 2. This is expected for an all-solid fiber that exhibits ultra bend insensitivity.

Our model easily allows to compute MPI spectra for any fibers and splice/connection losses in normal conditions. Despite different behaviors, we find that fibers 1, 2 & 3 exhibit MPI values for splices $<$0.1dB/splice well below the -30dB FTTH threshold $[8,9]$ in the 1240-1350nm window.

2.3 MPI Experiments

To check these findings, we have performed MPI measurements for splices $<$0.1dB/splice at 1550nm (see Figure 3). Theoretical and experimental results show very good agreement above the -60dB measurement noise threshold (see Figure 3). As expected, the MPI level is far below -30dB over the 1240-1350nm range, which demonstrates that any 2m STAF patchcord exhibits an outstanding behavior with respect to splice-induced MPI.

To further investigate this tolerance, extreme conditions ($>$1dB/splice at 1550nm) have been considered. In this configuration, the manual offsets to get the targeted splice losses after fusion become important. The overlap-integral approach is no longer sufficient to accurately model the coupling between the $LP_{01}$ and $LP_{11}$ modes at the connections.
FTTH Threshold (-30dB) 
Measurement Noise (-60dB)

Figure 3: MPI spectra under normal conditions (<0.1dB/splice).

If theoretical data are not available in this case, experimental results are shown in Figure 4. These extreme conditions generate higher MPI levels at which we better see the different MPI behaviors between:

- Same fiber type with different \( \lambda_{cc} \) (fibers 1 & 2): the curve slopes are similar but shifted in the order of their cutoffs.
- Different fibers with same \( \lambda_{cc} \) (fibers 2 & 3): the curves slopes are different due to different LP\(_{11} \) leakage losses evolutions with wavelength (see Figure 2).

Even under these extreme conditions, which would be rejected in standard FTTH deployments, all fibers show a good tolerance with MPI levels lower than -30dB in the 1260-1350nm range.

Figure 4: MPI spectra under extreme conditions (>1dB/splice).

Note that intermediate conditions (between 0.1 and 1dB/splice) give intermediate results between those obtained under normal and extreme conditions, which confirms the good MPI tolerance of STAFs.

2.4 Conclusion

In normal use (<0.1dB/splice), a very good agreement between theoretical and experimental results has been obtained. Excellent MPI performance of single-trench-assisted BIFs at any wavelength longer than 1240nm (MPI<<-30dB) has been demonstrated. Single-trench-assisted UBIFs exhibit a different MPI behavior because of a weaker LP\(_{11} \) leakage loss dependence with wavelength. UBIF performance is still far below the -30dB FTTH threshold with values lower than -40dB in the same range as BIF.

In extreme cases (>1dB/splice), MPI performances are obviously altered but both STAF [1-4] offer good tolerances with worst-case MPI around 30dB at 1260nm.

Being compliant to G.652 specifications in term of cable cutoff wavelength (\( \lambda_{cc} <1260nm \)) therefore ensures a very high tolerance to MPI for any STAF deployed in FTTH networks.

3. Fusion and Mechanical Splicing

In addition to the improvements of fiber characteristics brought by G.657 ITU-T recommendations, compatibility issues with existing installation procedures or equipment are relevant aspects to consider. In that view, fiber spliceability is among the most critical property to investigate and is key for a trouble-free deployment of such fibers in the field or in optical components with reduced footprints.

In this section, we report insertion loss distributions for both single-trench-assisted BIFs and UBIFs, using fusion and mechanical splicers.

Mating two fibers first necessitates a fiber alignment operation, followed by the joint formation, be it either permanent (e.g. fusion splicing) or semi-permanent (such as connectors, mechanical splicing or fixed V-grooves). Numerous parameters contribute to the final insertion loss. One distinguishes intrinsic parameters such as Mode-Field Diameter (MFD) mismatch and fibers geometry to name but a few, and extrinsic parameters that are governed by equipment properties and performance (e.g. alignment method) or more simply end-user skills (e.g. for mechanical splices). Low insertion losses associated with high repeatability are thus highly desirable.

3.1 Fusion splicing

For fusion splicing, the presence of the surrounding trench in STAFs obliges to carefully check the two following aspects: first, the robustness of the fiber alignment and second, the applicability of the fusing conditions.

The first aspect is obviously only applicable to fusion splicer with core-alignment capability. On such machines, the fiber profile is analyzed using a transversal optical imaging system that produces an intensity pattern. By comparing to an internal set of fibers patterns, the splice is able to detect the fiber type and select the right fusing conditions. More generally, the system allows to accurately locate the core position and to compensate for fiber geometry. This way, highly repeatable alignment is obtained. Because of the trench, the pattern produced by STAFs is significantly different from those of SMFs, without compromising core visibility. Since there are numerous systems and splicer equipments, recognition of STAFs cannot however be always guaranteed on some old models. In such case, switching to clad alignment is always the safest solution. Most recent fusion splicers used are now compatible with the single-trench-assisted concept.

Fusing conditions are the second parameter to be assessed. As the joint is formed by an electrical arc discharge, the provided heat not only fuses the fiber glass but locally alters the refractive
index profile owing to thermally-induced diffusions of the dopants. Depending on fiber profiles and compositions, such local modifications can significantly degrade insertion losses due to excessive profile deformations (leading, for instance, to an increase of the MFD mismatch). This is particularly true when splicing different fibers types.

For both single-trench-assisted BIFs and UBIFs, the diffusion of the trench was not found to contribute to the final splice loss. Using standard fusing conditions set for SMFs can be recommended. Based on extensive splicing tests carried out with BIFs, average value below 0.04 dB at both 1310 and 1550 nm were obtained using 4 single-fiber splicers sets with standard SMF splicing conditions. Spliceability performance of single-trench-assisted BIFs with either G.652 fiber (or itself) is therefore comparable to that of standard step-index SMF (typically 0.02 dB).

3.2 Mechanical splicing

For mechanical splices, insertion losses are generally more sensitive to fiber geometry and MFD mismatch. This essentially results from the passive alignment system used within the mechanical splice.

Several splicing tests have been carried out on single-trench-assisted UBIFs. Fibers under test were selected by sampling the available population using both MFD and fiber geometry as selecting criteria. In Figure 6, we report the insertion losses distributions measured using 2 mechanical splicer systems (3M and AFL/Fujikura) when splicing UBIF to itself (128 splices), and to Standard SMF (50 splices).

At 1310 nm, an average loss value of 0.05 dB is reported for UBIF-SMF splice, and 0.04 dB when splicing UBIF to itself. Same averages values are found at 1550nm. These statistics are comparable with the typical performance specified for the 2 mechanical splicing systems when using standard SMF.

3.3 Conclusion

The splice loss statistics confirm the overall good spliceability of single-trench-assisted BIFs and UBIFs whatever the splicing system. Given the negligible contribution of the trench on the splicing performance, fusing conditions used to standard SMF are suitable for both BIFs and UBIFs. This property greatly facilitates practical FTTH deployment of such fibers. Choice of the most sustainable fiber alignment method is essentially governed by the specifications of the splicer model.

Splice loss statistics demonstrate an excellent compatibility levels with existing equipment. The homogeneous splice loss performance - whatever the fiber combination used for the splice (SMF, BIF or UBIF) is a strong argument towards an easier adoption of such fibers, making possible the development of reduced foot-print equipment.

BIFs have to be produced on a large scale in order to be compatible with the growing needs of the FTTH market. A robust manufacturing process is thus mandatory to ensure a tight control of all optical characteristics specified in the G.652.D and G.657.B ITU-T recommendations ($\lambda_{CC}$, bend loss, ...). All-solid single-trench-assisted profile is a simple structure that is well adapted to meet such requirements. Using our full-vectorial finite-element-method model, we have derived simple engineering rules that translate the required optical tolerances into index-profile tolerances. These rules are very efficient to get tight distributions of fiber characteristics and can easily be implemented in a manufacturing environment. Our PCVD process homogeneity has been optimized taking these rules into account. For UBIFs, more stringent specifications reduce the acceptable index-profile tolerances. The same method is applied to optimize the homogeneity of our PCVD process. In this case, this is well adapted to low-volume manufacturing.

To illustrate the robustness of our optimized process, we present some distributions of single-trench-assisted BIF and UBIF.

$\lambda_{CC}$ is a key parameter for BIFs and UBIFs: it has to be below 1260nm (upper limit of G.652.D) and above a certain value to ensure sufficiently low bend losses. For single-trench-assisted BIFs, when $\lambda_{CC}$ is lower than 1170nm, it becomes difficult to stay compatible with G.657.B bend-loss specifications. Figure 7 shows the $\lambda_{CC}$ distributions of our single-trench-assisted BIF and UBIF (Figure 7). They demonstrate the excellent control of this key parameter.

![Figure 7: Cable-cutoff-wavelength distributions of single-trench-assisted BIF (top) and UBIF (bottom)](image)

Bend-loss distributions at 7.5mm bend radius at 1550nm are presented in Figure 8. Single-trench-assisted BIF presents far better performances than what is specified by the G.657.B ITU-T recommendation (<0.5dB/turn). UBIF has bend losses three times lower than those of BIF and exceed the G.657.B ITU-T specification by one order of magnitude.

The bend-loss distribution at 5mm bend radius at 1550 nm of single-trench-assisted UBIF is presented in Figure 9. All fibers exhibit bend losses lower than or equal to 0.1dB/turn.

Polarization Mode Dispersion (PMD) distribution of single-trench-assisted BIF is presented in Figure 10. Again, excellent results in term of intrinsic values and distribution width are obtained. Concerning UBIF, the volume was too low to present reliable distributions. Based on first results, however, we do not expect any degradation compared to BIF.

At last, excellent loss distributions are obtained at 1625nm for the 2 fiber types (see Figure 11). Note that UBIF presents a slightly but statistically significant better performance than that of BIF.

![Figure 8: Bend-loss distributions at 7.5mm bend radius at 1550 nm of single-trench-assisted BIF (top) and UBIF (bottom).](image)

![Figure 9: Bend-loss distribution at 5mm bend radius at 1550 nm of single-trench-assisted UBIF](image)
5. Conclusion
Our most recent studies on all-solid single-trench-assisted BIFs and UBIFs made with the versatile PCVD platform have been presented in this paper. Excellent performances are reported: no MPI degradation when the cable cutoff wavelength is kept below the upper limit of G.652.D ITU-T recommendation, securing the use of such fibers in FTTH networks; excellent spliceability behavior and backward compatibility with standard step-index G.652.D SMFs; and tight control of all optical performances.

STAFs are mature products that can reliably be manufactured on a large scale, compatible with the growing needs of the FTTH market, and with tighter specifications adapted to new component intra-connection and specialty applications.

6. References

7. Pictures of Authors

L.-A. de Montmorillon graduated in optics engineering from Sup’Optique (Orsay) in 1993. He received a Ph. D. degree from the university of Paris-Sud in 1997 for a work devoted to photorefractive ultrasonic detection. He then joined Alcatel in the fiber optic R&D unit. Since 2004, he has been working in Draka Communications on new telecommunication fiber designs.

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