Paper

Testing of highly doped and photonic crystal optical fibers

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Abstract—The paper presents optical measurements – spectral loss, OTDR and PMD, temperature cycling and mechanical tests – bending, twist and crush, performed on Yb-doped single mode fibers and small-core photonic crystal fibers (PCF). Several issues related specifically to characterization of such specialty fibers, like measurement errors and artifacts as well as coupling of test instruments to samples are presented. Of particular importance is reliable and low-loss fusion splicing of specialty fibers to standard single mode fibers (SMF), as most commercially available fiber test instruments are fitted with SMF interfaces only.

Keywords— highly doped fiber, photonic crystal fiber, measurements, testing, polarization mode dispersion, birefringence, mechanical testing, temperature cycling, optical fiber splicing.

1. Introduction

As the development of specialty fibers progresses and their applications in optical amplifiers, fiber lasers, dispersion compensators, sensors, wavelength converters, etc., become more numerous, characterization of such fibers gains importance. Designs, geometry, operating wavelengths and optical parameters of specialty fibers are often very different from those typical for fibers used in telecom networks, for which established measurement techniques, standards and instrumentation have been developed. In addition, new designs are steadily added and standardization is generally lacking. This forces researchers to develop novel testing techniques and ways to test non-standard fibers with existing instruments. An important problem is splicing of specialty fibers to standard single mode or multimode fibers and reduction of splice loss.

All experiments presented in this paper were carried out at the laboratories of National Institute of Telecommunications (NIT) as part of participation in the COST Action 299 "Optical Fibres for New Challenges Facing the Information Society" (FIDES)[1], dedicated to new applications of fiber optics. This includes extensive research and characterization work on new fiber designs, in particular highly doped fibers (HDF) for lasers and amplifiers and photonic crystal fibers (PCF) for sensing and signal processing.

Fiber samples provided by other participants of COST-299 for characterization included:

- Ytterbium-doped, silica-based single mode and multimode fibers intended for high power optical amplifiers, with optical pumping and amplification at wavelengths of 976 nm and 1060 nm, respectively. Those fibers are made commercially by nLight (formerly Liekki Oy), Finland using an unique direct nanoparticle deposition (DND) process and have very high Yb content of 1200 ppm.
- Highly nonlinear "holey", or photonic crystal fibers with small core strongly doped with germanium, supplied by IPHT Jena, Germany.

While the tests were aimed at establishing fiber characteristics such as optical loss, uniformity, polarization mode dispersion (PMD), thermal and mechanical properties, a separate problem of importance was optical coupling between measuring instruments and samples under test.

2. Measurement set-up

2.1. Optical connections to test instruments

Most instruments in our lab, except for optical power meters, had optical interfaces tailored to testing of single- or multimode telecom fibers with standardized cladding diameter of 125 μm and core size of either 5–10 μm or 50–62.5 μm, fitted with optical connectors.

Our preferred approach was to fusion splice the sample of specialty fiber to short (approx. 2 m) lengths of best-matching telecom fiber – either non-dispersion shifted single mode (ITU-T G.652, IEC B1) or 50/125 μm multimode (ITU-T G.651), terminated with FC/PC connectors.

Attempt to connectorize PCF fiber by gluing and polishing has failed: dust created during polishing has filled holes and could not be removed, introducing loss of over 30 dB. Adapters for cleaved fiber could be used, but were available for 125 μm clad fibers only.

2.2. Fusion splicing of PCF to standard single mode fiber

Splicing of single mode highly nonlinear PCF (Table 1 and Fig. 1) was challenging due to several factors:

– mismatch between core size of PCF and standard single mode fiber (SMF);

– different level of GeO_2 doping and refractive index of cores leading to Fresnel reflection;

– holes in PCF being easily be filled with any solvents used to clean the fiber;

– collapse of air holes when PCF is heated.

[1]See, http://www.cost299.org

Table 1
Comparison of PCF and SMF [1, 2]

Parameter	PCF (IPHT Jena 252b5)	SMF (Corning SMF-28)
Cladding diameter [μm]	80	125
Cross-section taken by holes [%]	18.2*	0.0
Cladding diameter after collapse [μm]	72	125
Core diameter [μm]	0.5/2.0**	8.2
Max. refractive index difference [%]	3.85	0.36
Mode field diameter (MFD) @ 1550 nm [μm]	5.8	10.4

* 90 holes of 3.6 μm diameter – see Fig. 1.

** PCF core has a triangular “pedestal” and inner “peak” of step profile.

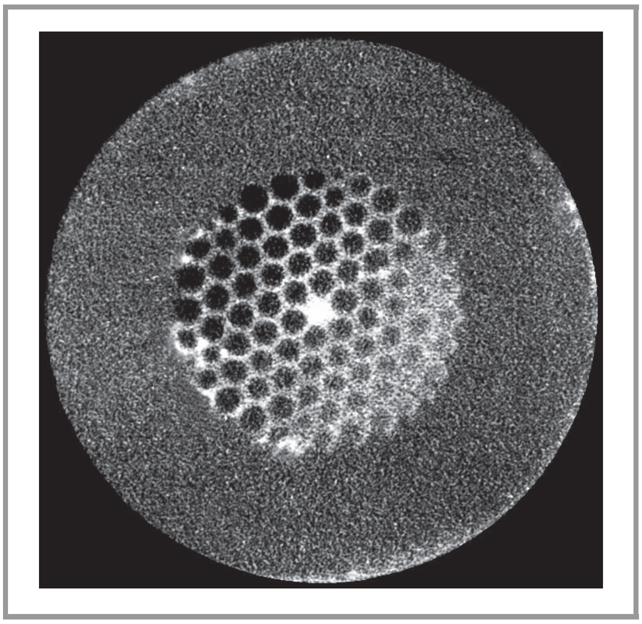

Fig. 1. Cross-section of IPHT Jena 252b5 highly-nonlinear PCF fiber (edited IPHT photo).

First attempts to fuse cleaved PCF and SMF routinely produced a bubble of 20–30 μm size at the interface, as some of the air from collapsing holes became locked there.

Cleaved end of PCF had to be pre-collapsed first (Fig. 2) by low-power electric arc, using current of about 12 mA with electrode spacing of 1 mm; this reduced PCF diameter by 10%. With some 100 μm of PCF tip collapsed, fusion splicing to SMF was made. This included: pre-fusion at 9 mA lasting 4.0 s, fusion at 16 mA with duration of 1.0 s and annealing at 8.5 mA for 3.0 s. To avoid deformation of thin PCF, fibers were put into contact approx. 150 μm away from the axis of electrodes, so most of arc power was transferred to bulkier SMF. Slices were protected with 60 mm long heat-shrinkable sleeves.

While this produced splices of satisfactory appearance and strength, the round trip SMF-PCF-SMF loss was very high: 32–50 dB at 1550 nm. The problem was traced to penetration of PCF holes by solvent (acetone) used to clean the fiber; it decomposed during fusion, leaving a dark, faintly visible carbon residue inside holes. This carbon and solvent locked in the holes produced strong light absorption.

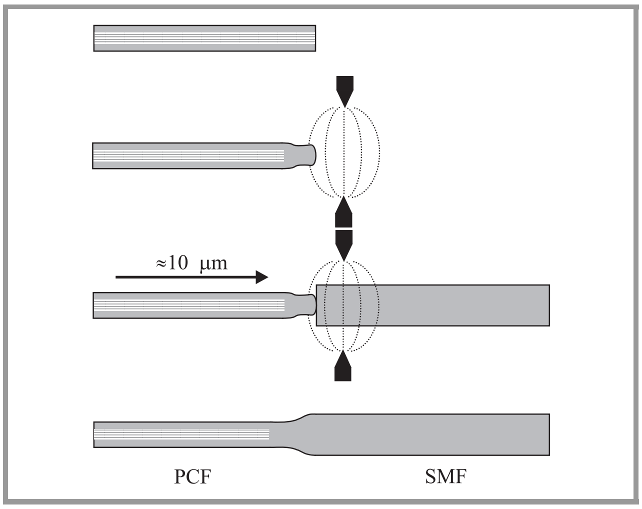

Fig. 2. Fusion splicing of PCF to standard single mode fiber.

In the next attempt, PCF tip was first melted in electric arc and sealed, then coating was softened by acetone bath lasting about 30 s, the fiber mechanically stripped, wiped with acetone-soaked tissue and cleaved. The SMF – 1 m PCF – SMF loss at 1550 nm went down to 15.8 dB. Excluding loss of connector (≈ 0.25 dB) and 1 m of PCF (≈ 0.05 dB), we get 15.5 dB for the SMF-PCF and PCF-SMF splices. Loss spectrum obtained with optical spectrum analyzer (OSA) and tungsten lamp (Fig. 3) shows weak OH^- absorption peak at 1380 nm and some reduction of loss with wavelength, as PCF mode field diameter increases.

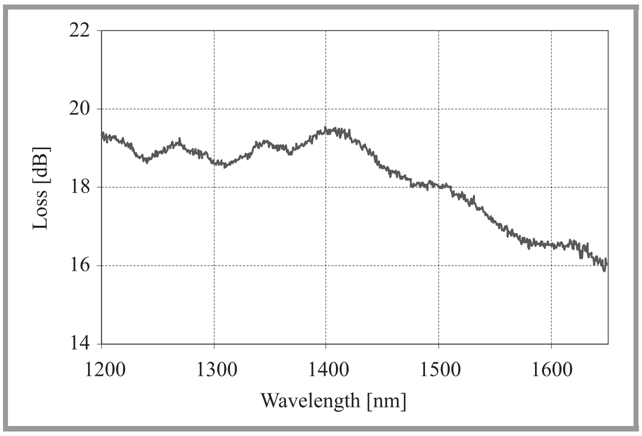

Fig. 3. Spectral loss of 1 m IPHT Jena 252b5 PCF spliced to 2 m long SMF pigtails.

Loss measured in our experiment was far higher than reported in [2], where optimized fusion splicing of identical PCF with collapse and rounding of fiber ends reduced

SMF-PCF-SMF loss to 3.2–4 dB. It was nevertheless acceptable for experiments on short samples.

Use of splicing procedure presented in [2] in our lab, with 0.5 s fusion duration and 18 mA current, followed by 3 extra heatings in the same conditions, gave an SMF – PCF – SMF loss of approx. 2.5 dB at 1550 nm. This work will be presented in a separate paper.

Splicing loss of incompatible fibers can be significantly reduced by introducing a short fiber with intermediate core size and refractive profile [3], but such fiber was not available. Another approach is to keep fusion time very short, typically 0.2–0.4 s [4, 5]. This prevents hole collapse and beam expansion inside PCF, but at the expense of splice strength.

2.3. Fusion splicing of Yb-doped HDF to standard single mode fiber

Two types of double-clad single mode highly doped fibers were tested: a small core (MFD = 6 μm at 1060 nm) Liekki Yb1200-6/125DC [6] and large mode area (MFD = 10 μm at 1060 nm), polarization-maintaining Liekki Yb1200-10/125DC-PM [7]. Both had cladding diameter of 125 μm and no holes, so a standard fusion splicer settings were adopted for HDF-SMF splicing. Fusion time was 1.5 s and arc current 17 mA; it was preceded by 5 s pre-fusion at 9.5 mA and followed by 3 s of annealing at 7.8 mA.

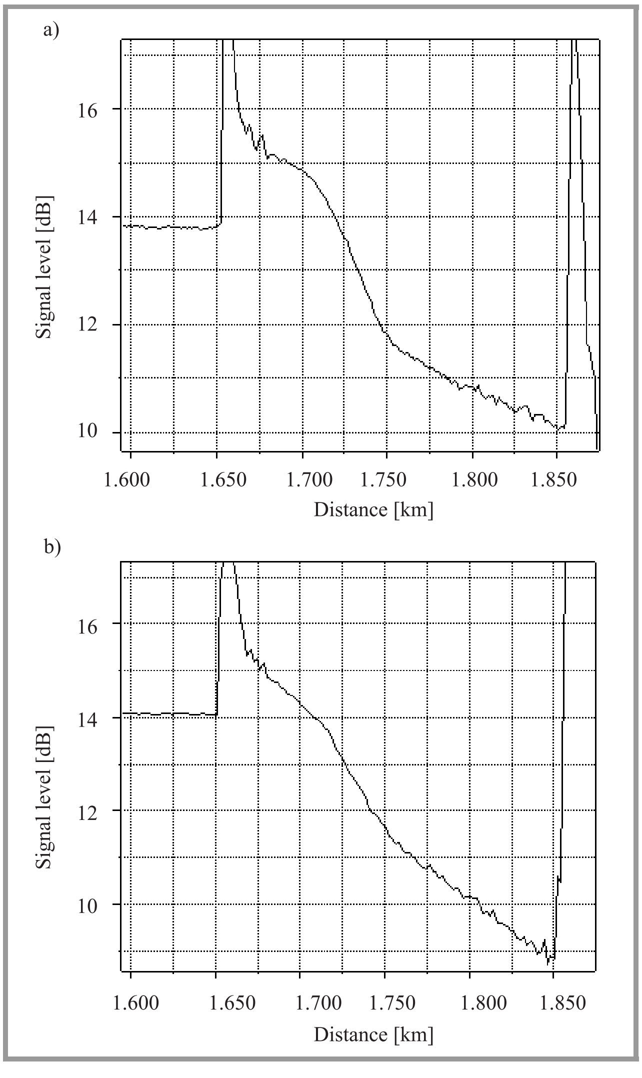

Fig. 4. OTDR traces of Yb1200-6/125DC fiber with SMF pigtail, connected to 1650 m of SMF: (a) $\lambda = 1310$ nm; (b) $\lambda = 1550$ nm.

Optical time domain reflectometer (OTDR) traces of SMF to HDF connection show that large part of light entering small core HDF (Yb1200-6/125DC) was forced into inner cladding. Cladding modes disappeared only after 100 m (Fig. 4).

Influence of cladding modes was less pronounced at 1550 nm, which can be explained by smaller MFD difference between fibers at this wavelength. Apparent connection loss resulting from fusion splice and FC/PC connector (on SMF) was 0.3 dB at 1310 nm and fell to –0.1 dB at 1550 nm.

Cladding mode effects and extended dead zone of attenuation measurement were absent in case of large mode area HDF, whose MFD was greater than that of SMF: ≈ 11 μm versus 9.2 μm at 1310 nm (Fig. 5). Apparent connection loss, however, was fairly high: 1.5 dB.

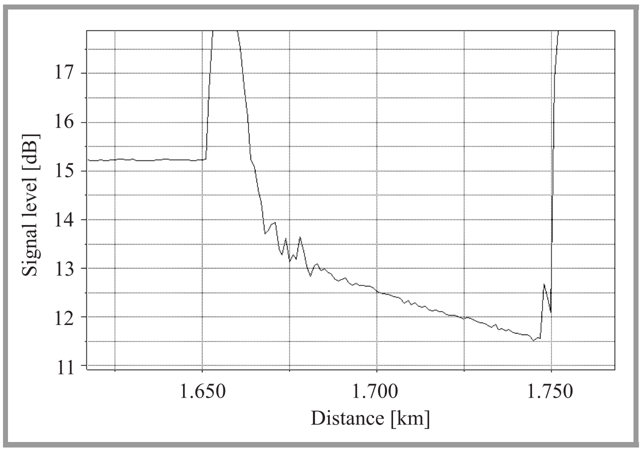

Fig. 5. OTDR trace of Yb1200-10/125DC-PM fiber with SMF pigtail, connected to 1650 m of SMF ($\lambda = 1310$ nm, pulse width 50 ns).

In summary, while fusion splicing of single mode HDF to SMF was easy, possible excitation of slowly-decaying cladding modes was detrimental to optical measurements.

2.4. PMD measurements

Polarization mode dispersion (PMD) in single mode fibers had been measured using alternatively:

- Jones matrix eigenanalysis (JME) method,
- fixed analyzer (FA) method.

Both methods are standardized for telecom single mode fibers [8], but applicability of them and particular instruments to testing of specialty fibers had to be verified. We have also tried to determine dependence of PMD on direction of light propagation.

For JME measurements, we have used an Adaptif Photonics (now Agilent) A2000 PMD analyzer and Agilent HP 8168F tunable laser source. Spectral range and resolution were 1460–1590 nm and 0.001 ps, respectively. The setup also measured other fiber parameters like polarization dependent loss (PDL) or second order PMD and their spectral distribution.

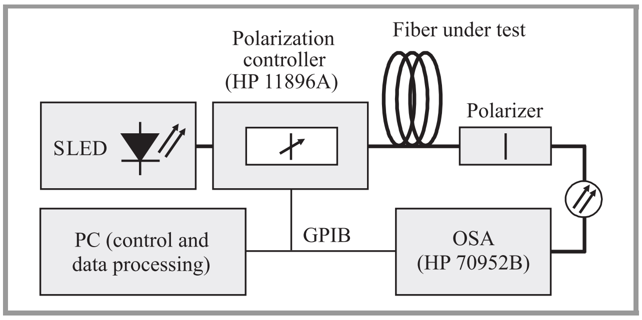

Fig. 6. Block diagram of PMD measurement setup using FA method.

The FA setup (Fig. 6) was assembled using off-the-shelf components. Instruments were controlled by a personal computer (PC) through the general purpose interface bus (GPIB). A superluminescent light emitting diode (SLED) source gave spectral range of 1250–1650 nm and resolution of 0.01 ps. This setup had a short measurement time of 5–20 s. However, FA method based on counting of extrema in transfer characteristics, while reliable, does not provide information on spectral distribution of differential group delay (DGD) or any other polarization-related fiber parameters [8].

3. Test results

Below are presented selected results of measurements and tests performed on HDF and PCF fibers, in particular those highlighting unique characteristics of such fibers and measurement problems encountered when established measurement methods were applied to characterization of those fibers.

3.1. Yb-doped fiber: Liekki Yb1200-6/125DC

Attenuation of this fiber (Table 2) could be measured non-destructively with reasonable accuracy only with OTDR, as this instrument enabled to select fiber section unaffected by propagation of cladding modes (Fig. 4).
Attenuation of this HDF was apparently dictated by Yb_2O_3 doping, not fiber defects. For comparison, loss measured in multimode HDF with the same dopant concentration (Yb1200-30/ 250DC) was 13.9 dB/km at 1310 nm.

Table 2
Attenuation of Yb1200-6/125DC fiber – OTDR test

Wavelength [nm]	Attenuation [dB/km]
1310	13.3
1550	26.1

Spectral loss characteristics shown in Fig. 7 was obtained with tungsten halogen light source and OSA. The sample was fusion spliced to SMF pigtails at both ends. As described in Subsection 2.2, this caused considerable excitation of lossy cladding modes. Attenuation measured this way is significantly overestimated, in particular at short wavelengths. For example, total loss recorded at 1310 nm was 5.75 dB. Subtracting connector loss of 0.25 dB and twice the splice loss of 0.25 dB, we get net fiber loss of 5 dB and attenuation coefficient of 28.6 dB/km, more than twice the value measured with OTDR.

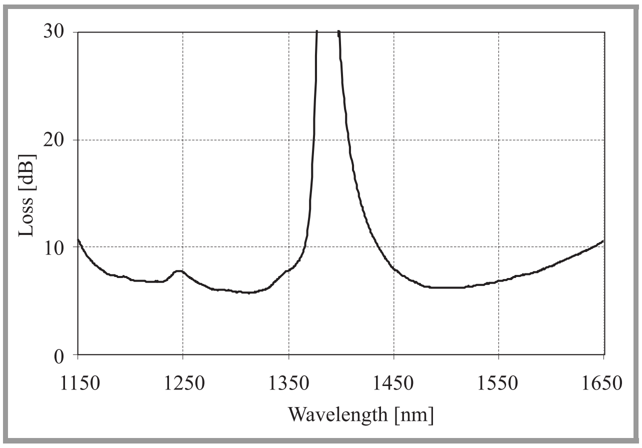

Fig. 7. Spectral attenuation of Liekki Yb1200-6/125DC fiber (length 175 m).

Accurate attenuation measurement using this setup would have required cutting off at least a 100 m long section of fiber to calibrate the OSA (see Fig. 4), making the measurement highly destructive.

Table 3
Polarization parameters of Yb1200-6/125DC fiber on 250 mm diameter spool – JME method

Parameter	Value
Fiber length [m]	200
Wavelength range [nm]	1480–1550
PMD (average DGD) [ps]	0.006
PMD coefficient [ps/km]	0.030
PDL (average) [dB]	0.03

Polarization properties were comparable to telecom SMF (see Table 3 and Fig. 8) with flat DGD spectrum. This indicates good control of fiber geometry and negligible forces exerted by coating.
Bending loss test, during which the fiber close to the end of 200 m length has been wound on set of mandrels, indicates low bending sensitivity (Fig. 9). Loss was measured with light emitting diode (LED) source and optical power meter. Loss instability was observed in several

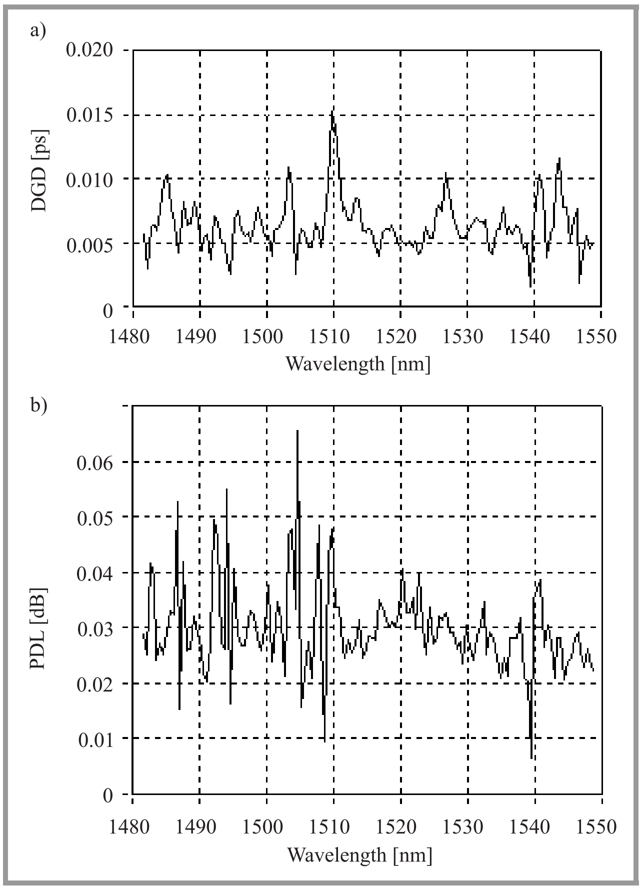

Fig. 8. DGD (a) and PDL (b) spectra (Liekki Yb1200-6/125DC, length 200 m).

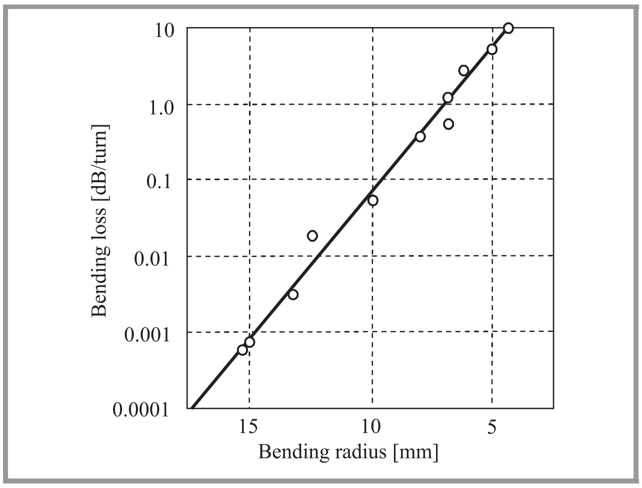

Fig. 9. Bending loss characteristics (Liekki Yb1200-6/125DC, $\lambda = 1300$ nm).

measurements, attributable to excitation of cladding modes, as the distance from mandrel to final splice before pigtail connected to power meter was only 1 m.

To investigate PMD created by bending (Table 4), a section of HDF approx. 2 m long was coiled on mandrels. This is a reasonable maximum length of fiber used in amplifier and usually enclosed in compact package.

Dramatic increase of PMD occurred when coil diameter was reduced below 45 mm; this bending limit is much stricter than dictated by loss. While the particular HDF is not intended for high-speed optical communication systems, erbium-doped fibers of similar design are likely to suffer from this problem, too.

Table 4
PMD introduced by bending (Yb1200-6/125DC, $\lambda = 1480$–1550 nm, total fiber length 200 m)

Bending radius [mm]	No. of turns	Length bent [m]	PMD [ps]	PDL [dB]
No bending	–	–	0.006	0.03
44	8	2.21	0.008	0.03
34	10	2.14	0.012	0.03
28	14	2.42	0.028	0.13
23	16	2.31	0.055	0.31
20	20	2.51	1.082	4.31
16	20	2.01	1.049	4.67

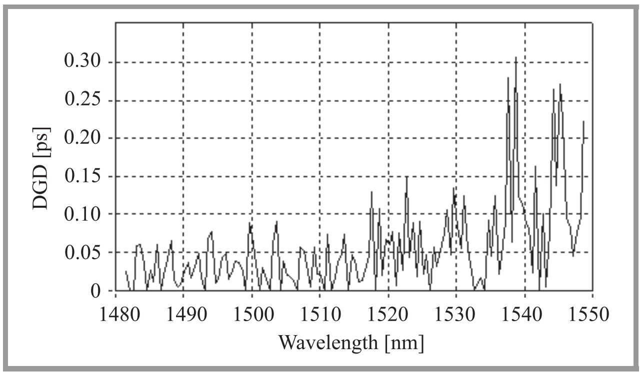

Fig. 10. DGD spectrum in Liekki Yb1200-6/125DC fiber bent at 23 mm radius

Such a great increase of PMD results from excitation of cladding mode(s), not strain-induced birefringence. This is confirmed by rapid increase of DGD with wavelength in threshold conditions (Fig. 10), caused by weaker guiding of fundamental mode at longer wavelengths.

Table 5
PMD introduced by crush (Yb1200-6/125DC, $\lambda = 1480$–1550 nm, total fiber length 200 m)

Crush force [N]	Pressure [N/m]	PMD [ps]	PDL [dB]
0	0	0.009	0.10
5	25	0.007	0.11
20	100	0.010	0.10
50	250	0.011	0.11
100	500	0.014	0.12

In another test, two parallel sections of PCF, each 100 mm long were crushed between flat steel plates. PMD variations were negligible until fiber coating was damaged when force reached 100 N (Table 5).

In summary, this type of HDF demonstrated excellent PMD performance, low bending loss and good quality of protective coating, but excitation of modes propagating in the inner cladding occurs easily when fiber is bent or spliced. Cladding modes propagate over long lengths.

3.2. Yb-doped fiber: Liekki Yb1200-10/125DC-PM

A 100 m sample of this fiber was used for COST-299 round-robin. Some results obtained at NIT will be presented here. This is a highly birefringent, double-clad, polarization-maintaining HDF fiber of PANDA design. Thanks to reasonable match of mode field diameter with telecom SMF (Corning SMF-28), there were no problems with splicing to SMF pigtails and related measurement artifacts. As the sample had to be delivered to other participants later in the same condition, mechanical experiments were ruled out.

Despite same level of doping, attenuation (Table 6 and Fig. 11) was higher than of Yb1200-6/125DC (Table 2 and Fig. 7). There is a strong OH^- absorption peak ($\approx$ 275 dB/km) and minimum of attenuation around 1300 nm. The tail of ytterbium absorption band is visible below 1150 nm.

Table 6

Attenuation of Yb1200-10/125DC-PM fiber – OTDR test

Wavelength [nm]	Attenuation [dB/km]
1310	20.6
1550	30.7

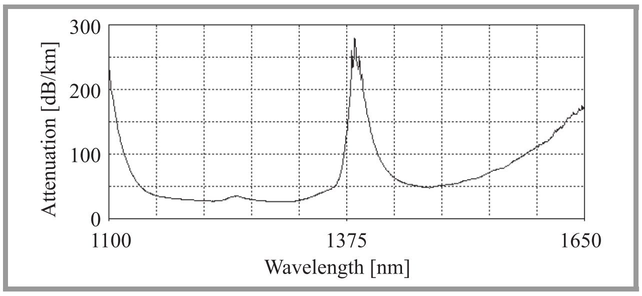

Fig. 11. Spectral attenuation of Liekki Yb1200-10/125DC-PM fiber.

Polarization properties were measured using both FA and JME methods, and for both directions of light propagation (see Table 7). Measured PMD values are in fairly good agreement with specifications [7] quoting birefringence $B \geq 1.4 \cdot 10^{-4}$, which corresponds to PMD of 467 ps/km. In a 100 m long sample, PMD was likely reduced by polarization mode mixing and true PMD coefficient may be higher.

Table 7

PMD of Yb1200-10/125DC-PM fiber on spool (fiber length 100 m)

Method	λ [nm]	Direction	PMD [ps]	PMD coefficient [ps/km]
JME	1500–1505	B-R	41.9	419
JME	1500–1510	R-B	42.3	423
JME	1500–1510	B-R	39.2	392
FA	1500–1505	R-B	42.5	425
FA	1500–1505	B-R	42.1	421

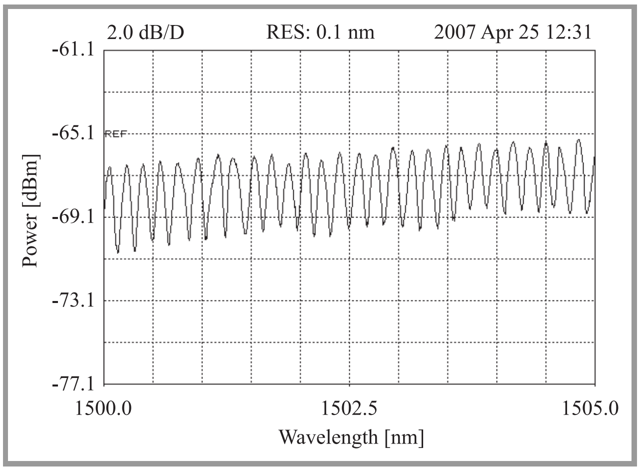

Fig. 12. Transmission spectrum in FA measurement (Liekki Yb1200-10/125DC-PM).

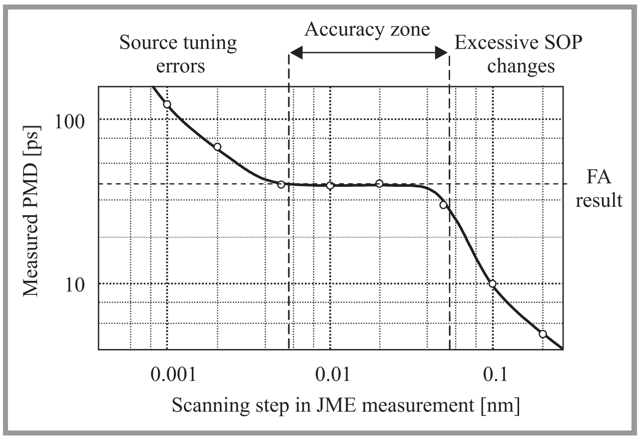

Fig. 13. Comparison of JME and FA measurements (Liekki Yb1200-10/125DC-PM, length 100 m).

While the FA method worked robustly, producing clear spectra (Fig. 12), PMD values delivered by JME analyzer depended on spectral scan step. Agreement with FA measurements was reached only in a certain range of settings (Fig. 13). This problem has been detected during tests of other fibers as well. It can be attributed to uncertainty of source tuning (HP 8168F) and possible "leaps" in detection of large shifts of state of polarization (SOP) when highly birefringent fiber is measured in large spectral intervals.

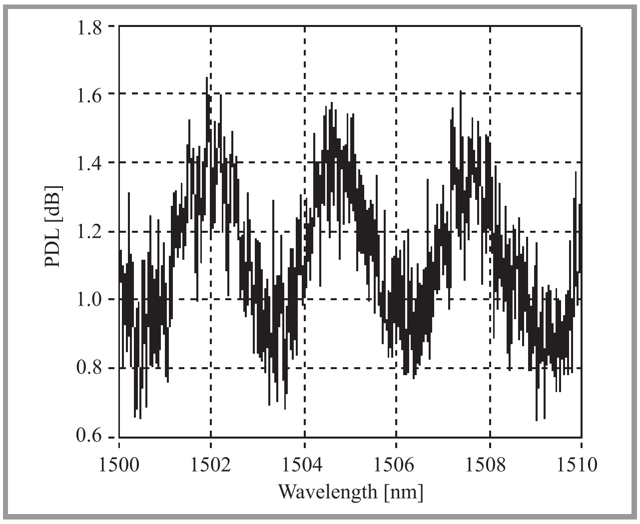

Fig. 14. PDL spectrum (Liekki Yb1200-10/125DC-PM, fiber length 100 m, direction R-B, scan step 0.01 nm).

Another interesting phenomenon was strong periodicity of PDL spectrum (Fig. 14).

3.3. PCF fiber: IPHT Jena 252b5

For this fiber, described in Subsection 2.2, PMD measurements (Table 8) and tests of influence of some external factors on PMD will be presented. A 17.1 m long sample was first tested during COST-299 round robin.

Table 8
PMD of IPHT Jena 252b5 holey fiber
(sample length 17.1 m)

Method	λ [nm]	Direction	PMD [ps]	PMD coefficient [ps/km]
JME	1500–1520	B-R	21.5	1257
JME	1500–1520	R-B	21.6	1263
FA	1545–1555	R-B	23.2	1357

As the fiber exhibits strong birefringence, samples about 1 m long were used for further experiments.

Despite very small fiber core, suggesting purely single mode propagation, spectrum recorded during FA measurements indicated quite strong polarization mode coupling (Fig. 15), which may be a consequence of fiber geometry imperfections. Spectral distribution of DGD measured with JME analyzer was remarkably flat (Fig. 16), unlike results from tests of ordinary single mode fibers. Average PDL of the 17.1 m sample spliced to SMF pigtails was low: 0.30 dB.

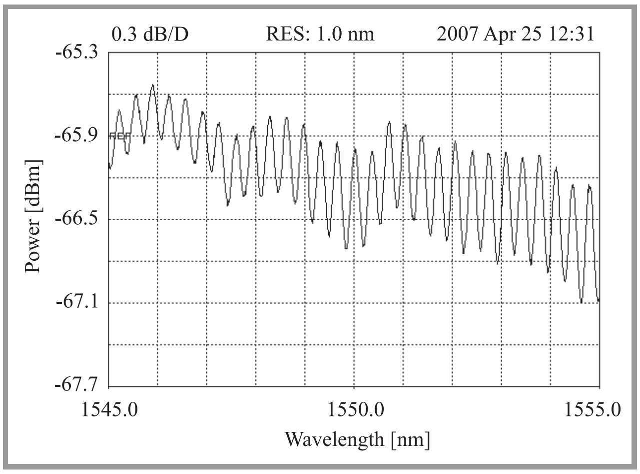

Fig. 15. Transmission spectrum in FA measurement (IPHT Jena 252b5, length 17.1 m).

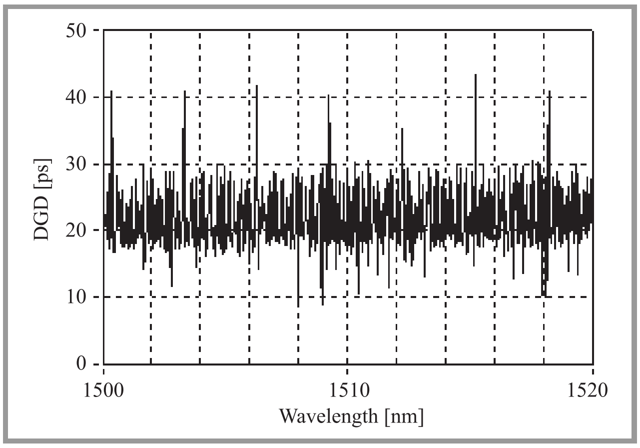

Fig. 16. DGD spectrum (IPHT Jena 252b5, fiber length 17.1 m, direction R-B, scan step 0.02 nm).

Rather surprisingly, PMD values obtained from JME and FA measurements have been in agreement for wide range of JME scan step between 0.002 and 0.1 nm (Fig. 17).

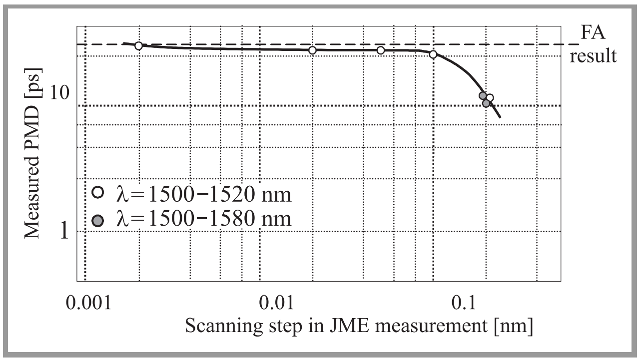

Fig. 17. Comparison of JME and FA measurements (IPHT Jena 252b5, length 17.1 m).

A 1.02 m long PCF was spliced to SMF pigtails, loosely placed on a flat plate and subjected to variable temperatures. This sample was taken from another length of PCF, which explains different PMD coefficient.

Table 9

IPHT Jena 252b5 – results of temperature cycling (fiber length 1.02 m, λ = 1480–1550 nm)

Temperature [°C]	PMD [ps]	PMD coefficient [ps/km]	PMD change [%]	PDL (average) [dB]
+20	1.104	1082	0.00	0.44
–20	1.100	1078	–0.36	0.46
0	1.102	1080	–0.18	0.42
+20	1.104	1082	0.00	0.45
+40	1.106	1084	+0.18	0.45
+60	1.107	1085	+0.27	0.52

Results (Table 9) indicate very low sensitivity of PMD to temperature; temperature coefficient was approx. $7.9 \cdot 10^{-5}$/K. For comparison, PANDA fibers exhibit temperature coefficients close to $9 \cdot 10^{-4}$/K.

Two other experiments on 0.82 m sample of PCF prepared in the same way were aimed at establishing effects of fiber bending and twist on its polarization properties. During the twist test, the fiber was kept straight at low tension. Splice protection sleeves were rotated against each other and twisted length of fiber was 0.80 m. Results are presented in Tables 10 and 11.

Table 10

IPHT Jena 252b5 – results of bending test (fiber length 0.82 m, λ = 1480–1550 nm)

Bending radius [mm]	No. of turns	Length bent [m]	PMD [ps]	PDL (average) [dB]
No bending	–	–	0.914	1.23
20	4	0.50	0.929	1.15
10	9	0.56	0.924	1.19
5	18	0.56	0.926	1.00

Table 11

IPHT Jena 252b5 – results of twist test (fiber length 0.82 m, λ = 1480–1550 nm)

No. of turns	Twist rate [rev/m]	PMD [ps]	Relative PMD	PDL (average) [dB]
0	0	0.914	1.000	1.23
16	20	0.874	0.956	0.93
32	40	0.749	0.819	0.81
48	60	0.663	0.725	0.86
64	80	0.590	0.646	1.03

Polarization properties of PCF were little affected by bending, and observed variations in PMD and PDL can be attributed mostly to measurement errors and problems with fiber handling.

Progressive twisting and resultant circular strain in fiber guiding area, however, resulted in steady, considerable reduction of PMD, although this effect was at least 100-fold weaker than in conventional single mode fibers investigated by the author [9].

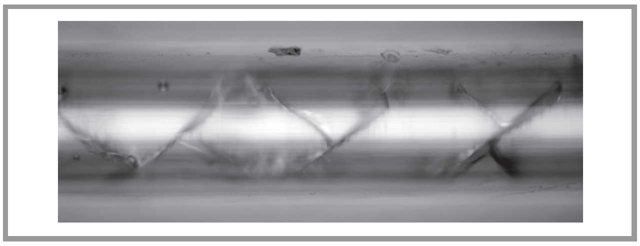

Fig. 18. Helical break in PCF cladding produced by excessive torsion.

When the twist rate reached 85 rev/m, the fiber was destroyed in a peculiar way: a section about 0.5 m long became soft and could elongate or bend with negligible stiffness; optical continuity was lost. Sample inspection with microscope revealed that a helical or double-helical break (Fig. 18) occurred in the cladding, but did not extend into the core.

4. Conclusions

Testing of PCF and HDF is difficult due to their unconventional optical and mechanical properties and difficulties with adopting commercial measuring instruments designed for testing of standardized telecom fibers. In particular, making a stable, low-loss coupling between specialty fibers of non-standard designs and core dimensions and test instruments requires additional work.

The PCF tested exhibited excellent stability of polarization parameters during mechanical tests and temperature cycling. This property and high PMD coefficient make it potentially useful for PMD etalons, e.g., for calibration of PMD analyzers or compliance testing of transmission systems.

Single mode HDFs, despite strong ytterbium doping, show PMD and bending performance comparable to standard SMF, proving good control of fiber geometry. However, dual cladding results in persistent propagation of cladding modes, causing severe problems during attenuation measurements.

Acknowledgements

The author is very grateful to our COST-299 partners, Kay Schuster and Jens Kobelke of IPHT Jena, Germany and Mircea Hotoleanu of Liekki – an nLight Company, Finland for supplying fiber samples.

Research work presented in this paper was financially supported by Polish Ministry of Science and Higher Education as special research project COST/39/2007.

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