Distributed Characterization of Low-loss Hollow Core Fibers using EDFA-assisted Low-cost OTDR instrument

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Abstract: We use a low-cost commercially-available Optical Time Domain Reflectometer (OTDR). Sensitivity is boosted by 28 dB using two EDFAs, enabling characterization with spatial resolution of 1.5 m, which is 10 times better than previously reported. © 2023 The Authors

1. Introduction:

Optical Time Domain Reflectometers (OTDRs) are widely used in the characterization of both newly-fabricated and deployed optical fibers [1] . The backscattering is relatively strong in traditional fibers (the fiber backscattering coefficient is typically -72 dB/m [2]), which makes it possible to test standard solid glass-core fibers (SMFs) with a high spatial resolution and dynamic range. However, emerging low-loss antiresonant hollow core fibers (HCFs) such as Double-Nested Antiresonant Nodeless Fibers (DNANF/NANF) [3] exhibit about 30 dB lower backscattering than SMFs, making OTDR characterization more challenging [4] . The first measurement of distributed loss using an OTDR in NANF was reported only recently [5] and used a high-end OTDR instrument with a very high sensitivity photon counting photodetector (LOR-200 from Luciol Instruments S.A., Switzerland). A spatial resolution down to 15 m (pulse width: 100 ns) was demonstrated.

Here, we show that the ultra-sensitive photon-counting detector is not necessary to measure OTDR signals in NANFs. We use a low cost commercial OTDR with a dynamic range well below that of top-end commercial instruments (30 dB vs 50 dB, e.g., provided an EXFO FTB-7600E instrument). Thanks to the low optical nonlinearity of DNANF/NANF [6] , we were able to boost the pulse energy launched into the fiber using an EDFA and thus increase the dynamic range of the measurement. In a preliminary experiment, we achieved OTDR measurements with a spatial resolution of 1.5 m, which is 10 times better than previously reported [5] .

2. Experiments

The experimental setup is shown in Fig. 1. To improve the overall sensitivity of the OTDR (FOTR-203 from FS.com, dynamic range given by the manufacturer of 30 dB) we boosted the power of the emitted pulses by > 28 dB prior to sending them into the fiber through use of a "Pulse Amplification" unit, Fig. 1 (a), in conjunction with two inline optical circulators which ensure the returning backscattered signal is routed directly back into the OTDR, Fig. 1.

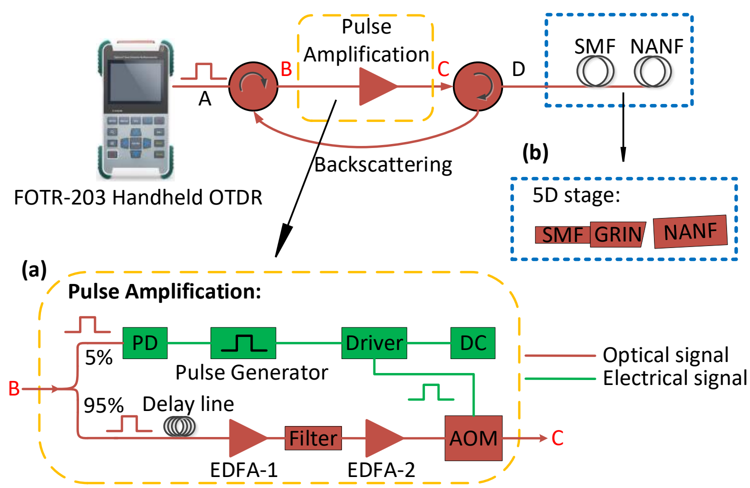

Fig. 1. Experimental setup showing the detail of the implemented Pulse Amplification unit (a) and detail of SMF-NANF light coupling (b). PD: photodetector, AOM: acousto-optic modulator.

The Pulse Amplification unit consisted of two off-the-shelf telecom EDFAs, Fig. 1 (a), with an optical bandpass filter incorporated in between them (passband of 1543 -1557 nm, which let pass most of the OTDR signaling 1550-nm Fabry-Perot laser power). The filter helps to reduce the build-up of amplified spontaneous emission (ASE) at 1530 nm. This 1530-nm ASE peak is particularly prominent when a low input power is used (the power input to the first EDFA was as little as -29 dBm). As the second EDFA works with a significantly larger input power (-5 dBm), ASE at 1530 nm generated by this second EDFA was relatively small. At the output of the Pulse Amplification unit is an acousto-optic modulator (AOM), which is used to reduce ASE noise generated in between the pulses (Fig. 1(a)).

The fiber under test (FUT) consisted of 509 m of SMF followed by 885 m of NANF (similar to the NANF used in [7]), which allowed us to compare the backscattering from both SMF and NANF. Low-loss (~0.5 dB) and low back-reflection (<-50 dB) SMF-NANF coupling was achieved using a mode field adapter based on a short segment of angle-cleaved OM2 graded index multimode fiber (GRIN) spliced to SMF at one end, with the other end butt-coupled to the flat-cleaved NANF via 5D-stages, as schematically shown in Fig. 1 (b). This approach is similar to that used in [5] and its performance is described in detail in [8] .

3. Results and discussion

Fig. 2 (a) shows the measured OTDR traces using the FOTR-203 OTDR both with and without the Pulse Amplification unit using 10 ns pulses (spatial resolution of 1.5 in NANF and 1.0 m in SMF). In Fig. 2 (a), we show the backscattered power (that decreases at a rate of about 0.4 dB/km for SMF) rather than backscattered amplitude (that decreases at a rate of about 0.2 dB/km for SMF) often used for convenience in OTDR instruments. We show backscattered power as it makes comparison of the performance using amplified and unamplified pulses more straightforward. The FOTR-203 without the Pulse Amplification unit shows a dynamic range of 14.4 dB for SMF, which is insufficient for use with NANF which is expected to have an almost 30 dB lower backscattering level [4] . Using the Pulse Amplification unit, the power was boosted by more than 28 dB, whereas the detection noise level stayed unchanged thanks to the use of the optical bandpass filter and the AOM in the Pulse Amplification unit (Fig. 2 (a)). This resulted in a significantly higher overall dynamic range of 14.4 + 28 = 42.4 dB for 10 ns pulses.

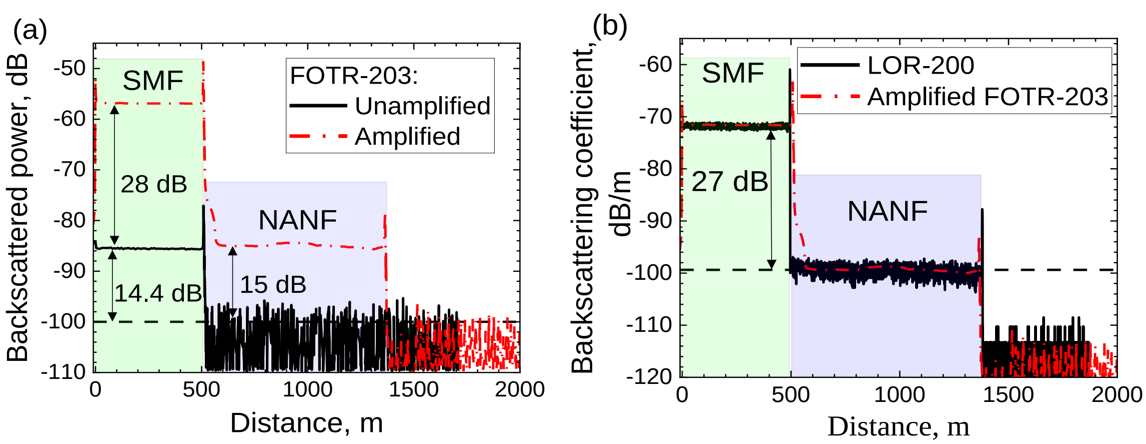

Fig. 2. OTDR traces using 10 ns pulses for a FUT consisting of 509-m SMF and 885-m NANF measured with the FOTR-203 both without and with the Pulse Amplification unit (a). For comparison, backscattering coefficients obtained from measurements with the Pulse Amplified FOTR-203 and with a high end LOR-200 OTDR without Amplification unit (upgraded version of that used in [5] are shown in (b).

The length-normalized backscattering coefficient α (dB/m) is obtained as [5] :

$$\alpha = P_b - 10\log\left(0.5 \times Pw \times v_g\right) + 15.0\,dB, \qquad (1)$$

where P_b is the relative power of the backscattered signal when the pulse width is Pw, the middle term represents the normalization to 1 m in fibers, and 15.0 dB is the calibration constant for the Pulse Amplified FOTR-203 setup, which we calculated from the SMF backscattering by considering a SMF backscattering coefficient of -72 dB/m.

Considering the loss introduced by the connectors and SMF-HCF coupling, we obtained:

$$\alpha_{SMF} = P_b - 10\log\left(0.5 \times Pw \times v_g\right) + 15.0\ dB + 0.4\ dB, \tag{2}$$

$$\alpha_{HCF} = P_b - 10\log\left(0.5 \times Pw \times v_g\right) + 15.0\ dB + 2.2\ dB. \tag{3}$$

As shown in Fig. 2 (b), the NANF backscattering coefficient is close to -99 dB/m, which is 27 dB lower than that of the SMF, a value that agrees with expectations as analysed in [4] and previous publication [5] .

Comparison of our result in terms of backscattering coefficient with that obtained with sensitive photon counting detection published earlier [5] (with the LOR-200 OTDR from Luciol) is shown in Fig. 2 (b). Both instruments (FOTR-203 with Pulse Amplification unit and LOR-200 without any Pulse Amplification unit) give almost identical backscattering coefficients. They also show comparable dynamic range. For FOTR-203, this was achieved thanks to our Pulse Amplification unit that boosted the pulse power without degrading the noise level. In this comparison (Fig. 2 (b)) we see a small ‘pedestal’ in the amplified FOTR-203 trace at the beginning of the NANF (distance of 500 m on the x-axis). This is caused by the relatively slow response of the AOM used (shortest pulses of 100 ns), which could be further reduced by using a faster AOM.

For the first time, we show here OTDR traces from NANF using standard photodetection. The FOTR-203 with Pulse Amplification unit enabled us to measure with 10 ns pulses with 30 seconds averaging time, which was significantly faster than with LOR-200 photon-counting, which without any Pulse Amplification unit required almost 1 hour to perform the same measurement with similar noise performance. It is worth mentioning that our LOR-200 is upgraded from the instrument used in [5] , explaining its better performance than previously published.

4. Conclusion

We showed that OTDR with standard low-cost photodetection is capable of measuring backscattering from NANFs (which is almost 30 dB lower than from SMF). In our preliminary demonstration, we used a low-cost OTDR in which we boosted the power of the pulses sent into the fiber under test. The boosted pulses enabled us to conduct the measurement with 10 ns pulses (spatial resolution in NANF of 1.5 m) with 30 seconds averaging time, which was significantly shorter than by using photon-counting (that required almost 1 hour to perform the same measurement with similar noise performance). We expect to be able to further increase the power into NANF (thanks to its high nonlinear threshold), further improving the spatial resolution and/or dynamic range, thereby enabling long lengths of NANF to be tested with high spatial resolution. This system is also of interest for distributed fiber sensing applications, where a higher received power allows for faster detection.

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