Optical Time Domain Backscattering of Antiresonant Hollow Core Fibers

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**Abstract:** Today’s lowest-loss hollow core fibers are based on antiresonance guidance. They have been shown both theoretically and experimentally to have very low levels of backscattering arising from the fiber structure – 45 dB below that of traditional optical fibers with a solid silica glass core. This makes their longitudinal characterization using conventional reflectometric techniques very challenging. However, it was recently estimated that when filled with air, their backscattering coefficient increases to about 30 dB below that of standard solid core fibers. This level should be measurable with commercially available high performance optical time domain reflectometers (OTDR). Here we demonstrate – for the first time to the best of our knowledge – the measurement of backscattering from the air inside a hollow core fiber. We show that the characterization of multi-km long hollow core fibers with 15 m spatial resolution is possible using a commercial OTDR instrument. To benefit from its full dynamic range, we strongly suppress the 4% back-reflections that ordinarily occur at the OTDR’s standard fiber output when directly-connected to a hollow core fiber. Furthermore, low coupling loss into the hollow core fiber (0.3 dB in our experiment) also helps to maximize the achievable OTDR signal-to-noise ratio. This approach enables distributed characterization and fault-finding in low-loss hollow core fibers, a topic of increasing importance as these fibers are now starting to be installed in commercial optical communication networks.

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1. Introduction

Hollow core optical fibers (HCF) which are now manufactured in km-lengths can achieve attenuation levels as low as 0.174 dB/km [1], and have been shown to be capable of transmitting data over thousands of kilometers in recirculating loop experiments [2]. Besides, they are beginning to be cabled and installed in ducts to carry live data traffic (e.g., by euNetworks [3]). To drive further manufacturing improvements, as well as to enable testing of HCF cables in the laboratory and in the field, it would be useful to be able to employ established distributed characterization techniques to identify fiber faults, manufacturing imperfections, or irregularities along the fiber length.

For today’s conventional optical fibers that have solid cores made of silica glass (such as standard single-mode fiber, SMF), optical time domain reflectometry (OTDR) is routinely used both in manufacturing and in installation environments. SMF typically produces a backscattered signal around -82 dB below the launched peak power for 1-ns long OTDR pulses [4], corresponding to backscattering coefficient of -72 dB/m [5]. In commercial instruments, this level of backscattering is compatible with the routine characterization of fibers of up to 400 km long (e.g., using the FTB7600 model from EXFO, Canada). The lowest-loss, data transmitting HCFs reported to date, of (Double) Nested Antiresonant Nodeless Fiber (DNANF and NANF) designs [1,6], however, have very low levels of backscattering due to their antiresonance guidance mechanism. It has been demonstrated experimentally [7] that the backscattering from the glass surfaces within the fiber structure is as low as -118 dB/m, over 45 dB lower than the backscattered signal in a typical SMF. This was measured using a custom-built optical frequency domain reflectometer (OFDR), which could measure backscattered signals as weak as -140 dB/m with a spatial resolution better than 1 m [7]. For a NANF with 0.22 dB/km attenuation [6], the power-limited measurement range of such an OFDR instrument is about 50 km. Unfortunately, such equipment is custom-built and currently not available commercially.

Recently, backscattering from antiresonant HCF was studied in detail theoretically [8]. Three backscattering contributors were analyzed. In comparing their (relative) magnitudes here, we refer to calculated values given at 1550 nm for a fiber with a core diameter of 35 µm [8]. The Rayleigh backscattering from the bulk glass in the microstructure was found to be very low (-150 dB/m), which is understandable given the very small fraction of the guided light propagating through it (less than 0.01% of its energy). The other two contributors were backscattering caused by the surface roughness of the glass microstructure surfaces (-115 dB/m) and Rayleigh backscattering from potential gases that may fill the HCF’s hollow regions (-100 dB/m for air at atmospheric pressure). Comparing the sensitivities among known reflectometric techniques would suggest the use of a phase-sensitive measurement technique such as OFDR or phase-OTDR [9] to measure such low levels of backscattering. However, when using these techniques, the thermal motion of gas molecules at room temperature must be considered. This causes Doppler broadening of the received signal, which ‘blurs’ the useful signal. As a result, the signal backscattered from the gas may not be detected (which was the case of the measurement reported in [7]), and only the (weaker) signal scattered from the static scatterers on the glass surfaces is measured. This offers the capability to measure the fundamental backscattering level that one would observe in an evacuated HCF. However, if the gas backscattering is of interest, e.g., to obtain a stronger distributed signal that is detectable with less sensitive systems, or to study the longitudinal gas pressure/composition itself, phase-sensitive instruments (such as OFDR) would require a careful setting of the measurement parameters in order to capture the gas-induced Doppler broadened signal correctly. Such a measurement technique has not, to our knowledge, been reported yet.

To measure the backscattering inside antiresonant HCFs, we suggest the use of a high sensitivity OTDR, the standard implementation of which is not phase-sensitive and thus insensitive to Doppler broadening in the moving gas. As Rayleigh backscattering from the air inside an antiresonant HCF was recently predicted to be stronger than surface scattering (by about 15 dB as discussed above [8]), we estimated that the sensitivity of a top-of-the-range OTDR should be sufficient for its detection. From the fiber characterization point of view, this represents using a less sensitive method (OTDR vs OFDR) to measure a stronger signal (air scattering vs surface scattering), resulting in a low or no overall loss of the signal-to-noise ratio. It also enables the use of commercially-available instrumentation. An additional advantage is the polarization insensitivity of most OTDRs as compared to phase-sensitive methods, directly providing a measurement of the total scattered power, which is the information of interest in routine fiber characterization and testing.

Commerically-availabe OTDR instruments have already been used for characterization of HCFs [10], including antiresonant HCFs [11]. However, the distributed backscattering signal has been collected only for photonic bandgap type HCFs [10], which have backscattering level from the fiber structure comparable to that of solid-core silica fibers [8]. For antiresonant HCFs, however, OTDR traces in the literature (e.g., [11]) only show the reflection from the fiber ends with no distributed backscattered signal (that is below the noise level) along the antiresonant HCF length.

Consequently, there has been a discrepancy between the predictions (distributed backscattering level [8] that should be measurable with commercially-available OTDR instruments) and experimental results (no such backscattering shown so far).

Here, we report on findings that enabled us to successfully measure the distributed backscattering in antiresonant HCFs. We found that one of the keys for a successful OTDR measurement of antiresonant HCFs is careful handling of the coupling loss and of the strong back-reflections that otherwise happen at the interface between SMF pigtail to the OTDR and the input facet of the HCF under test. Without an efficient suppression of this 4% back-reflection, the measurement is limited by saturation due to the strong initial reflection peak rather than by the sensitivity of the instrument. Further, the OTDR spatial resolution needs to be reduced to enable low level of backscattering to be measured above the noise floor. In our demonstration, we used a commercially-available OTDR based on sensitive photon-counting detection (LOR-200 from Luciol, Switzerland), which provides sufficient dynamic range for pulses of 1 µs duration (spatial resolution in HCF of ~150 m) [12]. We also use the SMF-HCF low back-reflection, low-loss coupling approach presented in [13]. To further improve the signal-to-noise ratio, we measured NANF HCFs that are relatively long (over 4 km), enabling us to use longer pulses (lower spatial resolution, but better signal-to-noise ratio). We estimate a backscattering coefficient of -101 dB/m from the measurement data, which is very close to the predicted value [8]. Finally, we demonstrate the ability to identify isolated scattering events along the fiber, most probably caused by isolated fiber imperfections, down to a spatial resolution of 5 m.

1. Simulations

To provide context and to justify the use of an OTDR technique we quantify, through simulations, the backscattering contributions of the various sources previously identified and assess the potential to measure these with different measurement systems. In an OTDR measurement of a fiber having a backscattering coefficient *B*, the power reflected from a 1-m length section of fiber situated a distance *z* away from the launch end of the fiber is given by:

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| --- | --- |
| , | (1) |

where τ is the pulse width, *vg* the group velocity in the fiber, is the launched power and a the fiber attenuation. In [8], it was shown that the backscattering coefficient *B* in antiresonant HCFs depends mainly on the core radius R and wavelength and is relatively insensitive to the antiresonant HCF microstructure. The backscattered contribution due to surface scattering was found to scale with 3/R6, while the contribution from the gas inside the hollow core follows 1/(R)2.

Fig. 1 and Fig. 2 show the calculated backscattered coefficient *B* defined in Eq. (1), obtained by following the mathematical development and procedure described in [8] for a NANF-type hollow core fiber similar to the one used in our experiment. In these calculations, we considered fibres filled with air at atmospheric pressure. It is worth mentioning, however, that manufactured fibers may have pressure or gas composition different to this, which we discuss in Section V. In Fig. 1, the core diameter was set to 36 µm, close to the diameter of our experimental NANFs and close to that of the NANF reported to have the record-low NANF attenuation [6]. Fig. 2 shows the backscattering at the wavelength of 1550 nm used in our experiments for different core sizes. As can be seen, the Rayleigh backscattering from the atmospheric air inside the fibers is expected to be well above the predicted surface scattering across a wide spectral range and for all practical ranges of core diameters. Simulations suggest an air-dominated Rayleigh backscattering at the -100.7 dB/m level at 1550 nm and for a core diameter of 36 µm. In terms of the change in backscattering level with core diameter, Fig. 2, we see that for a ±1 µm deviation in core diameter about 36 µm, the backscattering coefficient is expected to change by ±0.35 dB/m.



Fig. 1. Calculated Rayleigh backscatteringcoefficient *B* from atmospheric-pressure air-filled NANF hollow core (black solid) and backscattering coefficient due to glass surfaces within the microstructure (red dashed) as a function of wavelength for core diameter of 36 µm.



Fig. 2. Calculated Rayleigh backscattering coefficient *B* from atmospheric-pressure air inside the hollow core of a NANF (black solid) and backscattering coefficient from the glass microstructure surfaces (red dashed) as a function of core diameter at the wavelength of 1550 nm. The average core diameter of experimentally-used fibers of 36 µm is marked with a black dashed line.

1. Experiment

For the OTDR measurement, we used a field-deployable, LOR-200 (Luciol Instruments S.A., Switzerland), which uses sensitive photon counting photodetectors. Thanks to its sensitivity, backscattering from a NANF filled with air at atmospheric pressure should be measurable. From its test report, our OTDR has a backscattering dynamic range of 25.5 dB in terms of backscattered amplitude (square root of the backscattered power) for an SMF at 1550 nm when the longest (1 µs) pulses are used. Although OTDR instruments often show backscattered amplitude (to enable straightforward one-way fiber loss calculation), we use backscattered power throughout our manuscript. In terms of the backscattered power, our OTDR dynamic range is then 51 dB (2 x 25.5 dB). From Eq. (1), it follows that the relative backscattered power () at (beginning of the fiber) for t =1 µs pulses should be -52 dB for SMF (*B* = -72 dB/m) and -79 dB for NANF (core size 36 µs, B = -100.7, Fig. 2). Thus, backscatter signal from NANF is expected to be about 27 dB weaker than from SMF. Given the instrument dynamic range for SMF of 51 dB with 1 µs pulses (spatial resolution of 150 m in NANF), we should be able to measure backscattered signals in a NANF filled with air at atmospheric pressure that are 24 dB above the noise floor (27 dB lower than for SMF). Measurements at 10 times better resolution (15 m) should generate signals up to 14 dB above the noise floor.

The second limiting factor in an OTDR measurement is the maximum difference between the strongest and weakest signals that can be measured, which is typically 30-50 dB, depending on the OTDR instrument and the measurement settings. When measuring NANF, this requires careful management of the 4% reflection (-14 dB) that typically happens at the interface between SMF (i.e. at the OTDR input pigtail) and NANF, as light travels through the associated glass/air boundary. For a 1 µs pulse, the back-reflection peak at -14 dB is 38 dB above the SMF backscattering level (-52 dB for 1-µs pulse) and 65 dB above the expected backscattering level in the NANF (-79 dB for 1-µs pulse), preventing measurement of the NANF backscattering level. To suppress this back-reflection, we used an 8o-angle-polished solid core fiber [13]. This suppressed back-reflection at the input to the OTDR to below -60 dB. To further reduce the insertion loss (by 0.15 dB), we also applied a simple four-layer anti-reflective (AR) coating [13]. It is worth mentioning that we also tested an easy-to-prepare angle-cleaved fiber with -49 dB back-reflection without any anti-reflective coating and found it to be sufficient for the collection of backscattering data. Our angle-cleaved fiber was a short piece of OM2 graded index multimode fiber which was then spliced on to the SMF. It served as a mode field adapter to expand the mode field diameter (MFD) from the 10 µm of the SMF to match the 24 µm MFD of the NANF [14]. The NANF and SMF (with the attached angle-polished [13] and AR-coated mode field adapter) were butt-coupled using 5D stages, Fig. 3. The SMF-NANF insertion loss was 0.3 dB and the coupling into the higher order modes of the NANF was kept to low levels, e.g., below -30 dB for the LP11 mode and below -20 dB for the LP02 mode (measurement described in [14]).

Graphical user interface, timeline

Description automatically generated

Fig. 3. Measurement set-up.

The two NANF samples used are geometrically similar: NANF 1 (4.3 km) has a core diameter of 35.4/37.0 μm at the beginning/end, while NANF 2 (3.4 km) has a core diameter of 35.3/35.8 µm. Scanning electron microscope (SEM) image of the end face is shown in Fig. 3. Further details are given in [15]. We measured transmission loss of these two samples at 1550 nm to be 2.0 dB (NANF 1) and 4.5 dB (NANF 2).

As shown in Fig. 3, we inserted 1 km of SMF prior to the NANF sample, which allowed for comparison of the backscattering from SMF and NANF.

1. Experimental results

Fig. 4 shows the measured trace of the 1-km SMF followed by NANF 1 (4.3 km) using 1 µs pulses. In all the results presented here, the light was launched from the input end of NANF 1 (core diameter of 35.4 µm). In this and in the following graphs, the distance shown on the x-axis has been adjusted considering the group refractive indices of a typical SMF (1.46) and NANF (1.003). We used 16 averages, which appeared to provide a good compromise between the acquisition time (several minutes) and smoothness of the measured curves. Throughout all of our measurements presented here, we used the minimum possible time between the pulses (limited by the pulse round-trip time through the fiber under test), which allowed us to measure up to 5 km of SMF or 7 km in NANF. In Fig. 4, we see that the backscattering signal of the end of the NANF 1 sample was 4.6 dB lower than at its beginning. To calculate the attenuation, we compared the backscattering level from the two ends of the NANF 1 sample. We presume the air pressure is close to 1 atm at both ends, as they are open to atmosphere. The output end of NANF 1 has slightly larger (by 1.6 µm) core diameter that its input end. Considering the rate of -0.35 dB/m/µm mentioned previously in the discussion of data in Fig. 2, we expect a decrease in the backscattering coefficient by about 0.55 dB/m at the output end due to the larger core diameter. The round-trip fiber loss is thus 4.6-0.55 = 4.05 dB, giving single-pass loss of 2.0 dB, which agrees with our transmission loss measurement of 2.0 dB. Both these measurements provide an average NANF 1 attenuation of 0.47 dB/km.



Fig. 4. Measured backscattered power normalized to the OTDR source peak power with 1 µs long pulses for 1 km SMF followed by the 4.3 km NANF 1 sample.

Fig. 5 shows measurements taken with different pulse widths of 100, 300, and 1000 ns. We see the expected decrease in the measured power by 10 dB for 10 times shorter pulses, while the noise level remains unchanged. The backscattering from the beginning of the NANF is about 20, 15, and 10 dB above the noise floor, which allows us to estimate the measurement range (e.g., up to 20, 15, and 10 km of fiber with 0.5 dB/km attenuation for these three pulse durations). For 1 µs, we earlier predicted a maximum dynamic range of 24 dB, which is about 4 dB higher than achieved experimentally. However, the predicted value did not take in to account the 0.6 dB return loss at the SMF-NANF interface, nor the return loss at the two FC/APC connectorized interfaces between the SMF patchcord and the OTDR, which we estimate to be 0.4 dB (0.2 dB one-way) each. Further, the instrument dynamic range is defined for minimum signal-to-noise ratio of 1, requiring signal to be 3 dB above the noise floor, explaining the remaining 3-dB difference. Thus, the practically obtained value of 20 dB is in good agreement with the expectations from the instrument’s test report. Considering a state-of-the-art NANF with a loss of 0.22 dB/km, this should allow measurement of 45 km of fiber at 150 m resolution. When measuring from both ends, this would allow the characterization of up 90 km of fiber.

Fig. 6 converts the data from Fig. 4, into a length-normalized backscatter g (in dB/m) calculated as follows:

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|  | (2) |

where is the backscattered relative power measured with 1 µs long pulses (shown in Fig. 4), the second term is normalization to 1 m in fiber, and 2.6 dB is the OTDR calibration factor, evaluated using a length of SMF with known backscattering coefficient. Additionally, we account for the insertion loss of 2⨯0.2 dB between the OTDR and SMF (round-trip loss through one 0.2-dB FC/APC connector) and 2⨯0.3 dB for round-trip SMF-HCF loss and 2⨯0.2 dB for round-trip FC/APC connector between the 1-km SMF and HCF samples, obtaining:

|  |  |
| --- | --- |
|  | (3) |



Fig. 5. Measured backscattered power with 1000 ns (blue, dash-dot), 300 ns (red, dash), and 100 ns (black, solid) long pulses for 1 km SMF followed by 4.3 km NANF 1 sample. The NANF attenuation that can be measured before reaching the noise floor is 20 dB for 1000 ns pulses, decreasing to 10 dB for 100 ns pulses.

In Fig. 6, we see that the backscattering from the SMF is at -75 dB/m, compatible with expectations for such a solid core fiber [4] as follows from Eq. (1) considering *B* = -72 dB/m. For the NANF, it is 29 dB/m lower than for the SMF, giving backscattering at -104 dB/m level, corresponding to (Eq. (1)) to *B* = -101 dB/m, in close agreement with the -100 dB/m expected from simulations.



Fig. 6. Backscattering normalized to 1 m long OTDR pulses of the 1 km SMF followed by 4.3 km NANF 1 sample. Backscattering power of SMF is at -75 dB/m power, while for NANF, it is 29 dB/m lower.

To further demonstrate the capabilities of the OTDR for NANF characterization, we also present here the NANF 2 sample, which was manufactured using the same procedure as NANF 1, but exhibits small manufacturing imperfections along its length. Fig. 7 shows the trace measured and processed in the same way as in Fig. 6, using 300 ns pulses to highlight the discrete features (as shown in more detail in Fig. 8). The first 400 m of the NANF 2 sample behaves similarly to NANF 1, with a backscattering coefficient 29 dB/m lower than for SMF, identical to the value measured for NANF 1. The total round-trip loss was 9 dB, indicating 4.5 dB one-way loss. This corresponds to an average NANF 2 loss of 1.3 dB/km, which is in good agreement with the attenuation measured via direct transmission loss. Along the length, we can identify several peaks, all of which produce backscattering levels well below that of SMF, thus representing very small backscattering events.



Fig. 7. Measured backscattering with 300 ns pulses normalized to 1 m long OTDR pulses for the 1 km SMF followed by 3.4 km NANF 2 sample. NANF backscattering coefficient: 29 dB/m lower than for SMF.

To investigate these localized scattering events further, we carried out two additional measurements. Firstly, we analyzed the trace at a higher spatial resolution (using 100 and 30 ns pulses). We restricted measurements to the range of 1.5-2.1 km (Fig. 7) where the biggest defects occur, as shown in Fig. 8. For comparison, we reproduce here also the 300-ns pulse measurement and show a 1-µs pulse measurement.



Fig. 8. Measured backscattered power over the selected region in NANF 2 sample using pulses of 30 (green solid), 100 (black dash), 300 (red dash-dot) and 1000 ns (blue dot) pulses.

With 30 ns long pulses (spatial resolution of 5 m in HCF) we can distinguish scattering features that were as close as ~4 m apart (e.g., around 1.59 km in Fig. 8). It is worth mentioning that although with 30 ns pulses the signal is close to the noise floor of the measurement, the scattering peaks rise well above the noise floor, enabling determination of their longitudinal location with an accuracy of ~5 m. We also see that the scattering events are visible already using 1-µs pulses, enabling their identification even from the fastest and highest dynamic range measurement.

The last test we performed was to launch light from the opposite direction to confirm the scattering points are static and that their identification does not depend on the direction of illumination. The result is shown in Fig. 9, where we see that the backscattering signal from isolated scatterers from both ends is perfectly symmetric, confirming the static nature of these points inside the fiber. As these features were always measured at the same places, they are most probably caused by scattering from defects in the glass structure. The origin of these imperfections will be subject of our further studies.



Fig. 9. Measured backscattered power over the NANF 2 sample using 300 ns pulses when illuminated in (a) forward and (b) backward (opposite) directions. To appreciate that all scattering features are at the same fiber position (the most prominent marked with dash-dot line), the x-scale of (b) is inverted.

1. Discussion

Both NANF samples show a backscattering coefficient of -101 dB/m, which is about 1 dB lower than predicted by simulations. Besides the accuracy of the measurements and simulations themselves, this difference could also be due to the air inside our fibers being at sub-atmospheric pressure, or having a composition different from that of atmospheric air. All of these are possible explanations [16]. The fibers were stored with sealed ends and operated with open ends only during the measurements. As gas filling a HCF of several km may take a very long time (even years), the gas pressure and composition inside may be relatively close to the ‘as-drawn’ fibers. During fiber drawing, the holes are pressurized with inert gas, suggesting the gas composition may well be different from atmospheric air. Due to the large temperature of the drawn preform, the pressure inside a cooled-down fiber may be well below 1 atm as recently observed and analyzed, e.g., in Ref. [16]. Yet another possible effect that may influence the inner pressure is the expansion of the glass microstructure during the fiber draw.

All measured data obtained with the NANF 1 sample show a small bump between 2.75 km and 2.95 km with an amplitude of about 0.7 dB (e.g., visible in Fig. 6). Based on the simulations shown in Fig. 2, the rise in the backscattering at that point might be explained by a reduction in the core size by about 2 µm, given the discussed rate of -0.35 dB/µm/m. Interpreting the data further, however, will require more theoretical and experimental work, as the loss and core size both contribute to the back-scattering changes.

With the NANF 2 sample, we see numerous backscattering events, all of which show a backscattering level below that of SMF. Judging from the backscattering level before and after each of these events, it seems that none of them adds significant attenuation. Thus, we can expect that any scattering point that adds appreciable attenuation to the fiber would be visible in the measured OTDR trace, confirming this measurement will be useful for fiber characterization and loss-point identification.

While the backscattering level is limited by the signal from the gas inside the fiber, we do not know a-priori, the pressure distribution of the air along the fiber length, and this may change the backscattering level. However, it seems that in the NANF 1 sample, the air is distributed relatively evenly along its length, enabling estimation of the fiber loss from the slope of the backscattering signal, similar to what is commonly done with SMF.

The above analysis suggests that OTDR could be used for the characterization of antiresonant HCFs in the same way it is used to characterize SMFs. And while we have restricted this discussion to the use of OTDR for fiber characterization, the same technique could also be used for distributed sensing along the fiber length. We expect that, based on our findings, OTDR could likewise become a useful technique for sensing variations in gas pressure or concentration along antiresonant HCFs.

OTDR has already been used to characterize antiresonant HCFs (length, major manufacturing faults, etc.), however, the backscattering from the air inside the HCF core has not been, to the best of our knowledge, shown. We see three possible reasons for this. Firstly, low-loss antiresonant HCFs with km lengths have been reported only relatively recently. Earlier measurements with shorter fiber pieces (100s of meters), required a finer spatial resolution (e.g., using 10 ns pulses), in which case the backscattering signal of air gets close to the instrument noise floor. Such a setting can however be useful to find the length of the fiber under test (e.g., as shown in ref. [11]), as the back-reflection from the beginning and the end of the fiber is more prominent when shorter pulses are used. The second reason is the loss in sensitivity that is caused by the strong (4%) back-reflection at the glass-air interface which occurs when launching light from a glass core fiber into the HCF, as already discussed. The third possible reason is the insertion loss of the input coupling caused by simple SMF-HCF butt coupling, which further reduces the overall sensitivity. Due to the MFD mismatch between the SMF and antiresonant HCF (typically 10 µm vs 24 µm at 1550 nm), relatively large loss (e.g., 3 dB, producing 6 dB loss for the return signal) is experienced, reducing the already weak backscattering signal to near or below the noise level. When cleaving SMF at an angle to suppress back-reflection, the insertion loss can be further increased, unless 5D stages are used to compensate for the angle, like we did in this work. In practice, we expect that a combination of all these effects, together with the prior lack of accurate simulations that predicted the expected level of backscattering (published only very recently), might have prevented the previously-published OTDR measurement traces for antiresonant HCFs from showing distributed backscattering along the fiber length.

1. Conclusions

We have demonstrated, for the first time, the feasibility of using a commercial OTDR for the characterization of attenuation in antiresonant HCFs, where the backscattered signal is generated by the air/gas inside the fiber. We have confirmed theoretical predictions of a backscattering coefficient of -100 dB/m, with only a 1 dB/m discrepancy versus the experimental measurements. We have reported measurement of fibers over 4 km in length with spatial resolution down to 5 m and demonstrated the ability to identify scattering events as close as several meters apart. We suggest such measurements could potentially be used to monitor the core diameter variation along the fiber length for fiber quality control purposes. Moreover, this measurement could be used to resolve the internal gas pressure along the fiber length – a useful diagnostic technique for a multitude of sensing applications. We show that OTDR can potentially be used to allow the characterization of HCF with lengths of up to 90 km (when tested from both ends). Given the commercial availability and field-deployability of the OTDR used, we believe that the measurement approach demonstrated in this work has the potential to find widespread use, as antiresonant HCFs start to be increasingly installed commercially. For manufacturers of commercial optical reflectometer systems who are targeting the burgeoning HCF market for their next-generation systems, we hope that this work demonstrates the need for high-sensitivity reflectometer systems which can collect both the quasi-stationary signals from glass reflections and Doppler-broadened signals from gas. For the manufacturers of antiresonant HCFs, we hope that this work will demonstrate a means to leverage the extremely useful length-resolved information of conventional OTDR testing for the characterization of HCFs. This provides a post-fabrication tool useful for the testing of cabled and installed fibers, and suggests new and interesting applications of the technique, for example, in distributed gas sensing.

**Funding**. This work was funded by the Engineering and Physical Sciences Research Council (EP/P030181/1), European Research Council (682724) and Royal Academy of Engineering.

**Data availability.** The data in this paper is accessible through the University of Southampton research repository [17].

**Disclosures**. The authors declare no conflicts of interest.

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