Optical side scattering radiometry for high resolution, wide dynamic range longitudinal assessment of optical fibers


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Abstract: Current optical reflectometric techniques used to characterize optical fibers have to trade-off longitudinal range with spatial resolution and therefore struggle to provide simultaneously wide dynamic range (>20dB) and high resolution (<10cm). In this work, we develop and present a technique we refer to as Optical Side Scattering Radiometry (OSSR) capable of resolving discrete and distributed scattering properties of fibers along their length with up to 60dB dynamic range and 5cm spatial resolution. Our setup is first validated on a standard single mode telecoms fiber. Then we apply it to a record-length 11km hollow core photonic band-gap fiber (HC-PBGF) the characterization requirements of which lie far beyond the capability of standard optical reflectometric instruments. We next demonstrate use of the technique to investigate and explain the unusually high loss observed in another HC-PBGF and finally demonstrate its flexibility by measuring a HC-PBGF operating at a wavelength of 2µm. In all of these examples, good agreement between the OSSR measurements and other well-established (but more limited) characterization methods, i.e. cutback loss and OTDR, was obtained.

OCIS codes: (060.2270) Fiber characterization; (120.5820) Scattering measurements; (060.4005) Microstructured fibers; (120.4825) Optical time domain reflectometry.

References and links

1. Introduction

The longitudinally resolved backscattering trace of an optical fiber is conventionally used to evaluate the performance of the fiber in terms of loss, possible localized defects and discontinuities in its transmission properties. Additionally, it provides insight into the quality and stability of the fiber's fabrication process [1, 2]. Backscattered light is used in commercially available instruments exploiting techniques like optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR) to evaluate the overall fiber integrity and loss as well as the interconnection and splice losses. The dynamic range and spatial resolution of these two techniques, however, whilst adequate for most mainstream telecoms applications, cannot fulfil the requirements of some special fibers, particularly for relatively high losses (~dB/km) and long lengths and when fine spatial resolution is required. One such example is that of hollow core photonic band-gap fibers (HC-PBGFs), which are of interest for low nonlinearity, low latency telecoms/datacom applications [3]. The current loss of HC-PBGFs, still limited to a few dB/km [4-6], combined with the requirement of multi-km transmission (for example for low latency data center interconnection) requires measurement dynamic ranges often in excess of 40-50dB. At the same time, the complex multistage fabrication process of these fibers, involving substantial manual handling of glass tubes and capillaries, is more prone to introduce undesired
contamination, e.g. in the form of particles and/or other imperfections, that can cause small-scale localized defects in the fabricated fiber and/or more extended regions of higher loss [7]. To improve the quality and production yield of HC-PBGFs, it is therefore essential to identify any such longitudinal defects, for which a spatial resolution of a few cm is required [7]. The combined dynamic range and resolution required in this case are far beyond the capabilities of current commercial optical reflectometry (OTDR and OFDR) systems.

Here we present a method to measure the longitudinally resolved optical out-scattered fiber power with high spatial resolution (~cm scale) and large dynamic range (>50dB). This data can then be used to infer information on the locally propagating signal and to obtain information on both local and distributed forms of loss. The method is validated through measurements on a standard telecoms fiber (Corning SMF28e) and subsequently used to examine a record-length 11km HC-PBGF, which to the best of our knowledge would not have been possible with any standard high-resolution reflectometry technique. We then use the technique to examine another HC-PBGF with unusually high loss and finally we demonstrate the flexibility of the method by measuring a HC-PBGF operating at a wavelength of 2µm, at which no commercial OTDR is currently available.

2. Optical side scattering radiometry

Backscattered power represents only a very small portion of the total light power out-scattered by a fiber. By way of an example, it is only ~0.13% in the case of commercial low loss single mode fibers operating at wavelengths around 1550nm [1]. In OTDRs and OFDRs, the light backscattered at a given position along the fiber length then has to travel all the way back to the fiber end in order to reach the detector. Therefore, it is further attenuated due to fiber loss and can also undergo other potentially undesirable propagation effects along its path. For instance, in a few-moded fiber such as a HC-PBGF, on its way back to the detector the backscattered power can be recaptured by a mode different from the one that has been initially excited, thus experiencing a different attenuation on its return path. All these issues, combined with practical limitations, e.g. on the maximum injected power and pulse width in OTDRs [1, 8], or the sampling frequency and wavelength range of the scan in OFDRs [9], limits in practice the performance of commercial instruments operating at a wavelength of 1550nm to the points/shaded regions shown in Fig. 1.

![Fig. 1. Visual representation of the dynamic range vs. longitudinal resolution of commercial reflectometry systems (> 70 instruments) as compared to the OSSR method described in this work. Different colors in OTDRs and OFDRs sections show different brands and instruments respectively. Point A refers to Luciol LOR-220 IR and Luciol v-OTDR and point B refers to Anritsu MW9087D, EXFO FTB-7600E, JDSU 8100D and Yokogawa AQ7285A. OFDR systems in this plot belong to Luna Technologies. The detailed list of devices analyzed for this figure is stored in the repository link provided at the end of Acknowledgment section.](image)
even finer spatial resolution but only at the expense of a low dynamic range and a reduced measurable fiber length, e.g. a resolution of 10µm over a length of up to 30m of fiber with an 18dB dynamic range. Currently, there is no commercial reflectometry equipment available operating at the 2µm wavelength range, and a system capable of characterizing the fabricated fiber for this wavelength region would be highly desirable given the recent interest in this waveband \([10, 11]\).

In this work we improve and automate a well-known characterization approach for the study of locally out-scattered light \([12, 13]\) to provide accurate length-resolved measurements of the out-scattered fraction of light from a fiber under test (FUT). We name this technique (longitudinally resolved) Optical Side Scattering Radiometry (OSSR). Figure 2 shows the schematic of the OSSR setup. The FUT is passed through an integrating sphere (IS) which collects the out-scattered light with a low noise detector. In our implementation, the FUT is re-spoled from one bobbin to another on a fiber-rewinding machine while light is coupled into the fiber via an arrangement incorporating a fiber rotary joint, shown in Fig. 3. This solution allows for low insertion loss (≈0.8dB), versatility (any source with fiberized output can be used for this measurement) and high stability (the rotary joint provides consistent coupling for a few hundred million rotations, removing any need for a small portable source on the rotating drum and allowing the use of a static standalone source), which are essential for this measurement. The maximum speed of the custom designed rotary joint device is ≈2000 revolutions per minute which allows a scan speed of up to 2km/min using a standard fiber spool with 1m circumference.

In order to track (and compensate for) any intensity fluctuations of the laser source, a small portion of the generated light is tapped out (e.g. by a 10/90 splitter) and monitored. The whole system is interfaced to a PC, which also collects readings of the scattered power and position along the fiber. The scattered light is locally detected and does not need to travel back along the fiber length, providing a better signal to noise ratio (SNR) as compared to an OTDR with a similar detector. This in turn increases the dynamic range. To achieve an even wider dynamic range the use of a lock-in amplifier could also be implemented \([1]\).

![Fig. 2. The setup of the proposed OSSR.](image)

![Fig. 3. The light coupling assembly: (a) the designed arrangement; (b) fabricated and installed on the rewinding machine.](image)
An optical amplifier is used to boost up the power injected into the FUT. Maximizing the input power will correspondingly increase the dynamic range of the system as its upper bound is determined by the absolute maximum collected power by the IS. This depends on the maximum handling power of the connectors and components as well as the scattering coefficient of the FUT, similar to OTDRs and OFDRs. The current rotary joint we use can handle up to 200mW, which sets the current upper power limit in our system.

The resolution of the measurement depends on the size of the IS, the sampling frequency and the rewind speed. The length of the IS determines the minimum possible spatial resolution. With a rewinding speed of $V$ and a sampling frequency of $F_s$, a spatial sampling interval of $X_s = V/F_s$ is obtained, which at low speed and high sampling frequency leads to over-sampling of the trace. At high rewinding speed and/or low sampling frequency, under-sampling occurs and therefore the resolution of the measurement is determined by the spatial sampling interval. Differently from other remotely operated reflectometry methods, OSSR requires access to the full length of the FUT and must therefore be applied before the fiber is installed, ideally during fabrication or immediately after it, when a newly fabricated fiber is re-spooled on its final bobbin.

3. Technique validation via a standard fiber at wavelength of 1.5µm

To configure our OSSR setup at the wavelength of 1.5µm, we used an off-the-shelf detector, attached to a ~5cm diameter 4-port IS with Spectralon coating (Newport calibrated IS, 819C-IG-2-CAL). The handling power range of this device is 100nW-2.5W. We optimized the light-collecting capability of the IS by improving the reflectivity of the ports and calibrated the device against several commercial low noise detectors. After calibration, we could detect light levels as low as ~100pW.

To verify the accuracy of the OSSR set-up we tested a standard telecoms single mode fiber. We used 3km of Corning SMF28e, which has a datasheet loss of $\leq 0.20\, \text{dB/km}$ at 1550nm. A tunable laser source (TLS) with +2dBm output power at 1550nm was used as the source. An Erbium doped fiber amplifier (EDFA) was used to amplify the light up to +7dBm. The FUT was collected on a bobbin with 0.5m circumference. The fiber input and output port of the IS were protected by long black tubes to avoid interference due to ambient stray light. Mechanical limitations of our rewinding machine set the maximum rewinding speed to 15m/min. The diameter of the IS sets the practical spatial resolution of our experiment to ~5cm. By adopting an integrating cube [13] or a sandwich-detector [14] arrangement to operate at this wavelength, or using a smaller IS the resolution can be further reduced. A frequency of 20Hz was set to over sample the signal with 4 samples per resolution length. Figure 4 shows the OSSR result with an inset showing a magnified part of the trace. Periodic noise at the revolution frequency of ~1Hz with an average amplitude of 0.4dB can be seen. This is an artefact generated by the rotary joint, which can easily be filtered out. The scattering trace shows a ~0.6dB linear power drop over 3km, which corresponds to ~0.2dB/km.

![Fig. 4. Scattering trace of the SMF28e. The inset shows a magnified part of the trace.](image)
For a more precise measurement, the loss can be estimated through the cumulative sum of the out-scattered power (CP) over the length of the measured fiber. For a fiber with loss factor of $\alpha$ (unit: dB/km) passing through an IS with $L_{IS}$ (unit: m) diameter, the CP (unit: W) can be expressed analytically via

$$F(x) = \frac{1}{L_{IS}} \int_0^x \left( \frac{-\alpha x + \beta}{10} \right) dx = \frac{10}{\alpha \ln(10)} \left( \frac{\beta}{10} \right) \left( 1 - 10^{-\frac{\alpha x}{10}} \right)$$  \hspace{1cm} (1)

Here, $\beta$ (unit: dB) is the out-scattered power at $x=0$. First, the CP is calculated from the measured OSSR trace, red curve in Fig. 5. The loss is then obtained by making a fit to the CP using Eq.(1) with $L_{IS}$ and $\beta$ known from the measurement and $\alpha$ as the fit parameter. For the fiber under test we obtained a loss value of $\alpha=0.20$dB/km, in good agreement with the fiber’s nominal loss value. The curve of $F(x)$ for $\alpha=0.20$dB/km, shown by the black dotted trace in Fig. 5, sits exactly on the calculated CP (a dB scale has been used for better visual representation). To demonstrate the sensitivity of the fit parameter ($\alpha$), two dashed lines corresponding to $0.20\pm0.02$dB/km (fiber’s nominal loss $\pm$ 10%) are also shown.

The calculation of the CP largely eliminated the periodic noise shown in Fig. 4 and removes the need for any filtering in the present case. Based on the level of input and out-scattered power, we estimated that at the wavelength under test, 78% of the lost power has been captured by the IS (the rest being absorbed by the glass and coating or not captured by the detector). This yields a fiber scattering coefficient of 0.91dB/km/µm$^{-4}$ that agrees well with the reported value of 0.94dB/km/µm$^{-4}$ [15].

Fig. 5. The CP of the out-scattered power. Inset: magnification of the second half of the trace.

4. Measuring the dynamic range using a record-length HC-PBGF

HC-PBGFs have a microstructured cladding made of sub-µm nodes connected by very thin glass membranes. Generally, a multi-step stack and draw technique is used for their fabrication, which has gone through tremendous improvements in recent years [3], resulting in a record length $\sim$11km HC-PBGF (cross section shown in Fig. 6(a)) with 5.2dB/km cutback loss and $>200$nm bandwidth around the central wavelength of $\sim$1550nm [6, 16]. This fiber is an interesting test-bed to demonstrate the dynamic range capability of our system. The high end-to-end loss of the 11km span ($\sim$57dB) means that conventional reflectometers can only probe a relatively short subsection of the fiber from each end, as shown later in this section.
For the OSSR measurement we used a high-power Er/Yb fiber amplifier with +26.5dBm power at 1560nm, 15m/min rewinding speed and 20Hz sampling frequency. The usable signal spans from -10 to -70dBm, providing ~60dB dynamic range in this test (see Fig. 7). As shown in the inset of Fig. 7, over the first ~30m the out-scattered power drops by ~10dB. This is believed to be mainly due to the mode mismatch between the launch fiber and the HC-PBGF, which results in excitation of higher order guided modes that have higher loss and hence scatter more than the fundamental mode, which explains the steeper slope at the beginning of the trace. As they lose power, after a certain length, the out-scattered trace becomes dominated by the fundamental mode. To couple light into the HC-PBGF, we spliced an angle polished connectorized single mode fiber attached to a suitable large mode area (LMA) fiber which acts as a buffer fiber that was then connected to the HC-PBGF using a specialized splicing recipe [17]. The mode field diameter of the buffer fiber and of the HC-PBGF are ~15µm and ~22µm respectively. With these input conditions, the OSSR result indicates that an accurate cutback loss measurement can be achieved only if the cutback length is longer than the transition length. We have found that coiling the fiber around a small diameter (~7mm) mandrel to strip out high order modes is effective in reducing this initial transition length to a few meters only [2].

Near the end of the fiber, the signal drops to below the noise floor and thus, to achieve an accurate measurement of the full fiber span we performed another test by swapping the launch
end around. Figure 8(b) shows the two combined traces (where for ease of visualization, the second trace has been plotted upside down, and with an arbitrary offset so that the two traces match up at the joint) alongside measurements obtained via a state-of-the-art OTDR which show a considerably reduced dynamic range (Fig. 8(a)). The OTDR set to provide the maximum dynamic range at a reasonable resolution (~15dB dynamic range and ~15m resolution). The measured OSSR loss achieved from the fit using Eq. 1 is 5.14dB/km, which agrees well with the measured cutback loss of 5.2dB/km (Fig. 6(b)).

A small number of features can be identified in the measured OSSR traces, including 16 discrete narrow scattering peaks (a magnified plot of one of which is shown in the inset of Fig. 8(c)). We speculate that they are caused by some small scale structural inconsistencies, the origin of which is currently under investigation using a number of techniques such as precision cleaving and fiber side-imaging with an IR camera [7] and X-ray tomography [18]. In any case, by using the procedure described below, we estimate that the cumulative impact of all the peaks on the fiber loss is <1dB (out of the 57dB of total measured loss). To calculate the loss of a peak, we integrate the out-scattered intensity along the length of defect and compare it with the scattered light from the clean section of adjacent fiber. Here, we assume coupling to other modes to be negligible. The assumption holds if the rate of change of the out-scattered power remains the same before and after the inconsistency point. Additionally, we also assume that almost all the lost light scatters out and is captured effectively by the detector. This is the case for HC-PBGFs, as the glass absorption (and the coating absorption) gives a negligible contribution to loss in these fibers. For example, in the case of the defect shown in Fig. 9, the total out-scattered power is 28.1µW over the defect length of 0.26m. The out-scattered intensity of the adjacent fiber section is 48.3µW/m. This implies that the defect out-scatters an amount of power equivalent to 0.58m of fiber. With the estimated fiber loss of 5.14dB/km, the defect loss is obtained:

$$\alpha_{\text{Defect}} = \frac{28.1 \mu W}{48.3 \mu W \text{m}^{-1}} \times 5.14 \times 10^{-3} \text{dB m}^{-1} = 0.003 \text{dB}$$

Fig. 8. (a) OTDR and (b) OSSR measurements of the 11km long HC-PBGF obtained by launching from both ends respectively. The inset (c) shows a magnification of a discrete scattering event.
This loss includes the actual loss of fiber over the defect length, which is $0.26m \times 5.14e^{-3}dB/m = 0.0013dB$. Therefore, the excess loss caused by the defect is $0.003 - 0.0013 = 0.0016dB$, which is extremely low. The effect of coupling to other guided modes will manifest itself by raising the scattering level and changing the rate of change of the out-scattered power; an example of which is discussed in the next section.

![Fig. 9. Analysis of the highlighted defect of Fig. 8(c) in the 11km HC-PBGF: (a) The cumulative power trace across the defect; (b) corresponding OSSR trace.](image)

We have identified that the structural deformation, which causes similar scattering points, happens only over a short fiber length (a few 10s of cm to a few meters) [7] which implies that fluctuations in fabrication control parameters are unlikely to be the cause of the anomalies. The multistage fabrication process of microstructured fibers increases the chance of incorporation of contamination and inconsistencies in the preform, which are the most likely origin of the point in the fiber. Depending on the size of the preform, and the expansion ratio, the length scale of the scattering points implies inconsistencies of the order of 10s to a few 100s of micron [18].

In addition to these localized peaks, wider peaks and troughs are also visible in the trace, indicating regions with a non-uniform scattering pattern, which likely correlate with small variations in fabrication control parameters like differential pressure or drawing speed, which we are investigating through a number of purposely developed techniques (e.g. [18]).

5. Demonstration of high spatial resolution in a high-loss HC-PBGF

While the consistency of HC-PBGF fabrication has improved considerably in the last few years, occasionally some fabricated HC-PBGFs still show a higher length-averaged loss (e.g. measured via the cutback technique) than expected. Their OTDR trace is often either clean or shows only a few small discontinuity points and therefore it cannot provide a clear explanation as to the reason for the high loss. Using OSSR, we can gain more information about the inconsistencies and issues within these defective fibers, one example of which is shown below. The transmission properties and cross sectional image of this high-loss HC-
PBGF are shown in Fig. 10. The minimum cutback loss is ~20dB/km, which is fairly high for this type of fiber, despite the fact that the cross sectional image in Fig. 10(b) does not show any obvious structural distortion. The transmission curve of the 300m length presents obvious anomalies if compared to the transmission curve of a 10m length, which suggests the presence of longitudinal defect(s). The OTDR traces in Fig. 11(a) and 11(d) indeed show some features, including a strong discontinuity near the end of fiber. Figure 11(d) shows the measurement in the opposite direction. To gain more insight we have also measured the fiber with OSSR at a wavelength of 1557nm (at which the cutback loss is ~37dB/km, as highlighted by the pink arrow in the figure).

Fig. 10. An example of a high-loss HC-PBGF: (a) the transmission properties of the fiber; (b) the SEM image of the cross-section showing a uniform and undistorted structure.

The OSSR results in Fig. 11(b) and 11c give a much clearer indication of the longitudinal problems in the fiber, showing more than 56 points with strong scattering (>3dB larger than the average intermediate scattering level). A comparison between Fig. 11(c), which is the measurement in the other direction, and Fig. 11(b) shows that all the scattering events are reproducible and the measurement is also robust in terms of identifying the scattering events. Additionally, the amplitude of like-to-like scattering events is different as the fiber properties on either side of the event, such as modal content and loss, are different. Moreover, there is a good agreement with the overall scattering pattern of the similar OTDR and OSSR traces. However, the pattern varies by changing the light coupling direction.

The features in the OTDR traces match very closely with some of the scattering events in the OSSR traces, however there are many other events that are not visible even at the finest resolution of our OTDR, showing the usefulness of the high spatial resolution and sensitivity of the OSSR. Here we emphasize another unique advantage of OSSR in the detection of possible non-isotropic scattering events, in particular those that do not backscatter the light and therefore can only be seen by OSSR and not by OTDR. This effect is independent of any spatial resolution.

It is noticeable that in this instance, the measurement does not start at zero and hence misses the transition at the coupling point (the transition region has been effectively reduced by the coiling technique introduced in section 4). Mechanical limitations of the rewinding machine that we used impose a dead-zone of ~2m right at the beginning and end of the fiber, where it is not accessible with the IS. With other rewinding machine designs, this can be reduced to as short as 0.5×L_{IS}. Additionally, the dead zone can be completely suppressed if the machine allows the spliced joint to pass through it. In this case, even an arbitrary sequence of different fibers can be examined.

As is clearly seen in the OSSR traces after the stronger defects, a raised out-scattered power is observed, indicating a defect-mediated coupling of light to higher order or cladding modes (HOMs/CMs). In the case of a weak coupling, the scattering level stabilizes after a few 10s of meters as the light coupled into the HOMs decays much faster. However, the set of
very strong scattering points near the end of the fiber (~230m) cause significant power coupling to the HOMs which dominate the out-scattered power trace and follow a faster decay rate. This mechanism was also confirmed in a separate time-of-flight experiment [19].

Fig. 11. Analysis via OTDR, (a), and OSSR, (b), of a high-loss defective length of a HC-PBGF. (c) shows the OTDR measurement in the opposite direction as compared to (a); and (d) is the OSSR result in the reverse direction as compared to (b). Wavelength is 1550nm for the OTDR (2ns pulse width) and 1557nm for the OSSR.

A figure of merit indicating the quality of these HC-PBGFs can be defined based on the number of scattering points per unit length. For comparison, the 11km fiber of Fig. 6 had 1.5
defects/km as compared to 206 defects/km for the fiber in Fig. 10. We have also observed that as
the value of the metric decreases (i.e. fibers with small number of defects/scattering points per
unit length), the intensity of the out-scattered light by each defect also seems to decrease
(i.e. the strength of defects weakens and the defects become overall less influential in the
transmission performance of the fiber).

6. Demonstrating the wavelength flexibility by measurement of an HC-PBGF at 2000nm

Besides the large dynamic range and fine spatial resolution, another advantage of the OSSR
technique is that it is readily extendable to perform measurements at other wavelengths. In our
setup, the IS has a Spectralon coating which provides very high reflectivity (≥95%) over the
wide wavelength range of 250nm to 2500nm. Thus, by using suitable sources and detectors,
measurements over this whole wavelength range can in principle be obtained. As an example,
we reconfigured the previous system to measure at wavelengths around 2000nm, the
wavelength of expected minimum loss for HC-PBGFs and promising for some future optical
data communications applications [11]. Whilst highly sensitive photodetectors for these
wavelengths are already commercially available in the market from different manufacturers
like Hamamatsu, Teledyne and EOS, for this demonstration we used a Mercury Cadmium
Telluride (MCT) camera that we had available in the lab. The MCT array detector is cooled
(thermoelectrically in 4-stages) to ~−63°C and had a cut off wavelength of ~2.7µm and a peak
sensitivity at 2.5µm. The detector array size is 320×256 pixels with 30µm pitch and 14-bit
data output. We bin all the pixels together to get a single large area detector. The fiber rotary
joint we used at 1550nm is still functional at the wavelength of ~2µm, albeit with slightly
more sensitivity to bends. The schematic of the setup is similar to the schematic in Fig. 2
except that the low noise photodetector is replaced with the MCT camera. We used a discrete-
mode laser diode [20] generating light at the wavelength of 1989nm followed by a Thulium
doped fiber amplifier (TDFA) as the source. We also used an extended InGaAs detector
(working over the wavelength range 1.2µm to 2.6µm, Teledyne J23-51-R02M-2.6) to monitor
the source power variation. We calibrated the detector at ~1.5µm and based on the
responsivity curve provided by the manufacturer we extrapolated the calibration factor at
~1989nm. The output of the camera is in analog-to-digital units (ADU) and is transferred to
the PC via a 16-bit bus. We calibrated the combination of the IS and camera by using the
extended InGaAs detector that we had calibrated earlier. We obtained a calibration factor of
4.58nW/ADU. The noise floor of this detector was found to be very sensitive to changes in
temperature, with a measured sensitivity of ±100ADU (0.46µW) per degree Celsius. Thermal
stabilization and measurement of the noise level was therefore necessary, particularly for low
light level measurements (i.e. for signals close to the noise level). The noise level of the
detector was in the several microwatts range. To improve performance here one could either
increase the SNR e.g. by using a coherent detection scheme, or use a more suitable detector
with a lower noise level and with less sensitivity to thermal fluctuations.

We tested a HC-PBGF designed to operate at a central wavelength of ~2050nm, with
195nm transmission bandwidth and a minimum cutback loss of 4.2dB/km at 2041nm.
Figure 12 shows the SEM image of the cross-section and transmission characteristics of the
fiber. Note that the test wavelength of 1989nm is sufficiently far from the surface mode group
[11] positioned around 1900nm. At the test wavelength the cutback loss is ~4.8dB/km. In this
test, due to our source limitations, the out-scattered light level is close to the noise level of the
detector. We used the coiling method to reduce the transition region at the coupling point
effectively. We allowed for the detector temperature to stabilize before the beginning of the
test and once stabilized we measured ~1260ADU (an equivalent of 5.77µW or −22.39dBm)
for the noise level. The result of the OSSR measurement including a suitable noise floor
calibration can be seen in Fig. 13. The fiber is seen to be almost defect-free over the 425m
tested length, with only a ~35m section at ~410m with a slightly increased out-scattered level
(not more than 2dB above the average). We estimated the loss of the fiber over its defect-free
region (highlighted by the blue line) to be 4.72dB/km, in very good agreement with the
cutback loss at this wavelength, which confirms that accurate distributed measurements can be also acquired at different wavelengths with relatively minor modifications to the set-up.

Fig. 12. An example of a HC-PBGF designed to operate at the wavelength of 2µm: a) the SEM image of the cross-section; b) the transmission properties of the fiber.

Fig. 13. The OSSR result of the 2µm HC-PBGF: The OSSR trace with the loss estimation over the clean section of the fiber.

7. Conclusions

In an effort to achieve long-range, high spatial resolution measurements of the longitudinal scattering pattern of HC-PBGFs we have developed a method, referred to as OSSR, which can measure the distributed loss of fibers with ~50mm resolution and ~60dB dynamic range, well beyond the capability of the best commercial fiber measurement systems. The characterization of virtually any type of special fiber and measurements at different wavelength ranges are possible. The method was validated in measurements on 3km of SMF28e, showing an accurate loss measurement within the tolerance of the manufacturer’s data. Then, the OSSR was used to measure a record-length (11km) HC-PBGF, providing for the first time accurate quantitative information about the longitudinal properties of these fibers despite the very large (~60dB) fiber span loss. Exploiting its high spatial resolution, which can provide detailed information on the presence/absence of small scattering points and defects along the fiber, the technique can also help to establish improvements in the fabrication process. As an example, the technique identified >200 scattering defects/km in a HC-PBGF with an unusual loss of 37dB/km, providing an explanation for the excessive loss of the fiber. A measurement at a wavelength of 2µm demonstrated the wavelength flexibility of the setup, with the ability to address wavelengths for which no commercial tool currently exists. Also in this waveband the loss estimate was in excellent agreement with cutback loss measurements. Finally, we believe that this method could ultimately provide an excellent solution for the longstanding issue of
fiber quality monitoring directly during the fabrication process of optical fibers [21], and future work will try to demonstrate its implementation directly on a fiber drawing tower.

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