Multi-kilometer Long, Longitudinally Uniform Hollow Core Photonic Bandgap Fibers for Broadband Low Latency Data Transmission

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Abstract—The low intrinsic nonlinearity and low signal latency characteristic of Hollow Core Photonic Bandgap Fibers (HC-PBGFs) have fueled strong interest for data transmission applications. Whereas most research to date has looked at improving the optical performance of HC-PBGFs (e.g., reducing the loss, increasing the transmission bandwidth and achieving well-tempered modal properties through the suppression of surface mode resonances). In this study, we address the challenging problem of scaling up the fabrication of these fibers to multi-kilometer lengths—an indispensable step to prove this fiber technology as viable. We report the fabrication of low loss, wide bandwidth HC-PBGFs operating both in the conventional telecoms window (1.55 μm) and in the predicted region of minimum loss (2 μm), in lengths that substantially exceed the state of the art. At 2 μm, we obtained a 3.85 km long fiber with $\approx$3 dB/km loss and >160 nm wide 3 dB bandwidth. Additionally, we report an HC-PBGF operating at 1.55 μm with a length of just over 11 km, transmission bandwidth in excess of 200 nm and a longitudinally uniform loss of $\approx$5 dB/km, measured via cutback and an integrated scattering method. We used the latter fiber to demonstrate error-free, low-latency, direct-detection 10 Gb/s transmission across the entire C-Band as well as 20 Gb/s quadrature phase shift keyed transmission. These represent the first demonstrations of data transmission over a length of HC-PBGF exceeding 10 km.

Index Terms—Fiber communications, hollow core, low latency, microstructured optical fibers, photonic bandgap fibers.

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I. Introduction

THERE has been a resurgence in interest in recent years in the use of Hollow Core Photonic Bandgap Fibers (HC-PBGFs) for telecommunication applications [1]. The primary driver is the potential for low-latency, guided-wave data transmission which is of huge interest in numerous time-sensitive application sectors including: intra- and inter- data center interconnection, high performance computing, large-scale high energy physics experiments, and for bespoke data networks for the financial sector in particular. For all these applications, the 1.54 μs/km latency reduction [2] offered by HC-PBGFs may represent a decisive advantage over existing and competing fiber technologies.

Remarkable progress has been attained in recent years in the development of these complex fiber waveguides. Whilst the unique enabling properties of HC-PBGFs, such as their low latency [2], low nonlinearity [3], low thermal sensitivity [4] and high radiation hardness [5] have been reliably confirmed, along with their ability to support broad-bandwidth (BW) high capacity transmission on the fundamental [6] as well as on multiple optical modes [7], most studies to date have used fiber samples of relatively modest lengths (typically less than 1 km). This has primarily been due to the difficulties in scaling up the fabrication procedures that are used to make such fibers (typically based on the so-called "stack-and-draw" method) [1], and in eliminating defects/contamination that can occur during preform manufacture [8], and also due to the lack of means to ensure that a sufficient structural uniformity is maintained along the full fiber draw. The demonstration that HC-PBGF can be reliably fabricated in long (multi-km) lengths has therefore emerged as one of the highest research priorities. Until long fiber samples become available to test in application trials of realistic scale, industrial and commercial interest in the technology will obviously remain limited.

In this paper, exploiting an improved understanding deriving from various new numerical and experimental fabrication and characterization tools that we have developed over the past few years, we report a significant step forward in HC-PBGF development. In particular, we have achieved what we believe to be

the first high performance HC-PBGF with a length in excess of 10 km, providing a combination of transmission BW (>200 nm) and loss (≈5 dB/km) that is close to the current state-of-the-art for much shorter fiber lengths. The longest fiber span obtained (11 km) was designed for operation at conventional telecom wavelengths (1.55 μm), however we also obtained multi-km long fiber spans operating at the wavelength of minimum loss for HC-PBGFs, i.e., ≈2 μm [9], [10]. In this instance, the longest fiber sample obtained was 3.85 km, which represents a 3.3× improvement in length for a HC-PBGF operating in this waveband [11]. A potential new "telecom window" at 2 μm would benefit from the recently developed thulium-doped fiber amplifier which offers gain BW greatly exceeding that of traditional erbium-doped fiber amplifiers at 1.55 μm [12].

In addition, we utilized the 11 km long HC-PBGF—a length compatible with many of the applications detailed above—to demonstrate the viability of 10 Gbit/s data transmission using direct detection with a simple return-to-zero ON-OFF keying (RZ-OOK) modulation and 20 Gb/s using the quadrature phase shift keying (QPSK) coherent modulation format. The propagation latency reduction in this fiber span as compared to a similar length of standard single mode transmission fiber (e.g., SMF28 or any non-zero dispersion shifted fiber) is confidently estimated to be in excess of 15 μs.

II. HC-PBGF FABRICATION UPSCALING CHALLENGES

HC-PBGFs are characterized by having a very complex structure and optical properties that are strongly dependent upon its fine details. Consequently, their fabrication, based on the stack-and-draw method, is substantially more involved as compared to that of conventional solid fibers. HC-PBGFs are obtained by manually assembling stacks composed of a few hundred capillaries with ≈mm diameter and a high geometrical consistency (at the ≈μm level); these are tightly packed and fused inside a glass jacketing tube and drawn into fiber using a two-step procedure [1]. Careful control of the pressure inside the holes (to ≈0.1 kPa) is paramount to tune the fiber structure to the target design and to maintain longitudinal consistency during the final fiber draw down step. Stack-and-draw is versatile (the capillary elements can be stacked in a wide range of geometries) and is at least partially amenable to automation; on the other hand, the process is rather slow and requires extensive manual handling, which often correlates with a higher likelihood of introducing stacking errors, defects and contamination within the preforms. The presence of defects and/or contamination within the preforms in turn leads to a higher fiber failure rate during the second stage drawing process, making it very challenging in practice to obtain long fiber lengths. Indeed, despite several groups worldwide attempting to improve HC-PBGF fabrication for several years, until very recently only a handful of reports of fiber spans of the order of ≈1 km had been reported in the literature [11], [13], [14]. Whilst conventional fibers are often fabricated at low tension in order to alleviate the incidence of fiber breakages and to maintain the integrity of the fiber over extremely long lengths of drawn fiber, this is often a less viable option for HC-PBGFs where it is imperative to minimize any structural distortions, which are promoted by a higher tempera-

ture/low tension drawing regime. HC-PBGFs are thus typically drawn at high tension (>200 g). It is therefore clear that the ability to produce first and second stage preforms as free as possible of contamination (e.g., by assembling stack in a clean, controlled environment) is of crucial importance. We have not only modified our preform assembly and processing to achieve this goal, but we also have applied a range of techniques, such as X-ray computational tomography, for the purpose of non-destructively investigating the quality of our preforms [8]. Furthermore, the presence of longitudinal inconsistencies in the fiber structure ("defects"), even of small amplitude and/or short characteristic length scale, may potentially lead to a significant worsening of the fiber's performance, for instance through increased scattering, by introducing undesirable coupling between optical modes supported within the core, or also by introducing surface modes at the defect point. These effects narrow the achievable BW, increase the transmission loss, and cause ill-controlled modal properties and excitation, and should obviously be avoided. We have previously presented the results of a comprehensive investigation of such defects in some of our fibers [15] and spent considerable effort in trying to link them to defects in the corresponding preform, to understand their origin and eliminate them.

Upscaling the fiber yield requires bigger canes and preforms to be used in both drawing stages ("caning" and fiber drawing). This may imply that one of the main benefits of a two-step procedure, i.e., reducing the draw-down ratio of each step as compared to an equivalent single-step procedure, would be partially lost. A lower draw-down ratio is beneficial as it allows a higher stress to be applied at the wide end of the glass body (preform) for a certain stress at the narrow end (drawn cane or fiber), while the maximum value of the latter is limited by the tensile strength of the glass [16]. This gives the opportunity to draw in a regime (higher stress through reduced temperature or increased feed rate) in which the microstructure has more lateral viscous stiffness and can thereby resist the distortions caused by surface tension [16], [17]. However, upscaling reduces the ability to achieve a higher lateral stiffness and thus has potential to bring about distortions within the microstructure [17]. Understanding the full impact of upscaling requires the development of precise fluid dynamic models, capable of capturing the evolution along the neck down region. These tools afford a much easier exploration of the draw parameter space [18] and have been employed in association with experimental observations to help narrow down the optimized draw parameter ranges which afford a minimization of structural deformations. These models indicate that stricter criteria for the precise balance between applied pressures and surface tension during the HC-PBGFs fabrication for bigger canes and preforms. Table I summarizes the main challenges relating to upscaling the yield per draw of HC-PBGFs along with the solutions we have identified and investigated.

III. FABRICATION OF MULTI-KILOMETER LONG HC-PBGFs

We report two record length, wide BW HC-PBGFs operating in the spectral regions at 1.55 and 2 μm, respectively. Both fibers have a 19 cell core (i.e., composed of 19 missing unit cells) and

TABLE I
HC-PBGF Upscaling Challenges

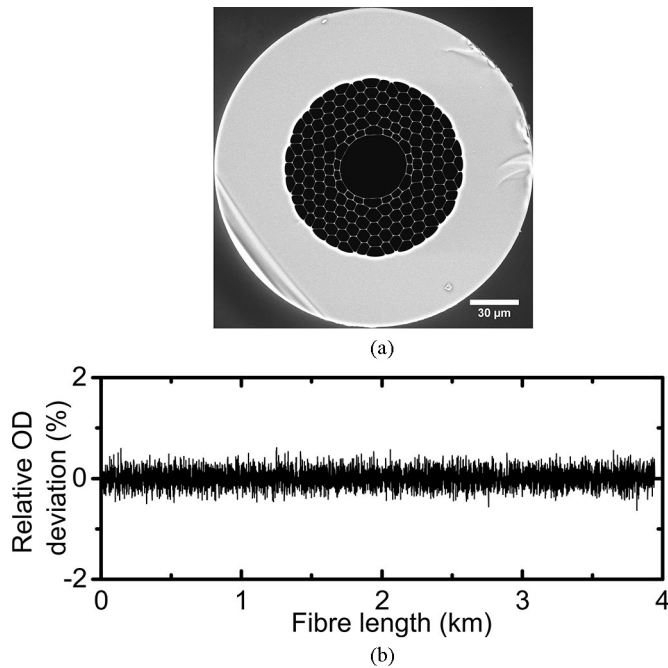| Challenges	Solutions
Eliminate fibre breaks	Optimize drawing tension – trade off with distortions
	Improve glass handling and processing
	Improve cleanliness of stacking process
Minimise longitudinal defects	Identify defects, trace them back to fabrication process and eliminate
Increase volume of glass, minimize distortions	Accurate balance between pressure and surface tension
	Fluid dynamic modelling
	Optimization of drawing parameters via "virtual draw"

(a)

(b)

Fig. 1.   (a) SEM image of the fabricated HC-PBGF operating at 2 μm; the fiber has a 19 cell core surrounded by five rings of cladding holes (plus an incomplete ring). (b) Diameter deviation versus fiber length measured during fiber drawing for the same fiber.
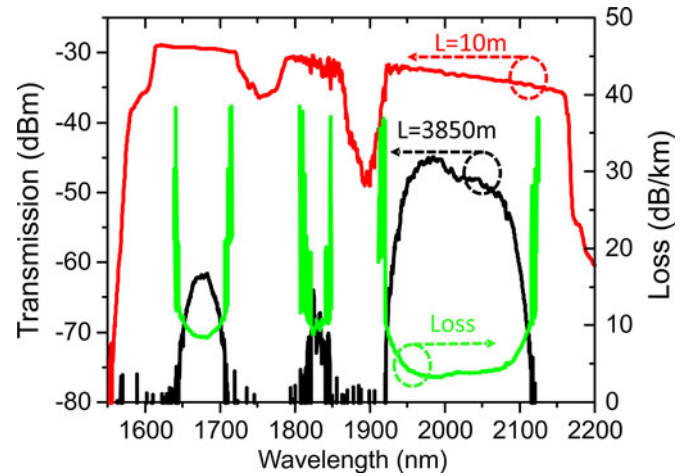

Fig. 2.   Spectral attenuation of the 2 μm HC-PBGF, measured from a 3.85 km long cutback. Note the very wide bandgap (1550–2175 nm) segmented into three windows (widest is >160 nm) by surface modes.
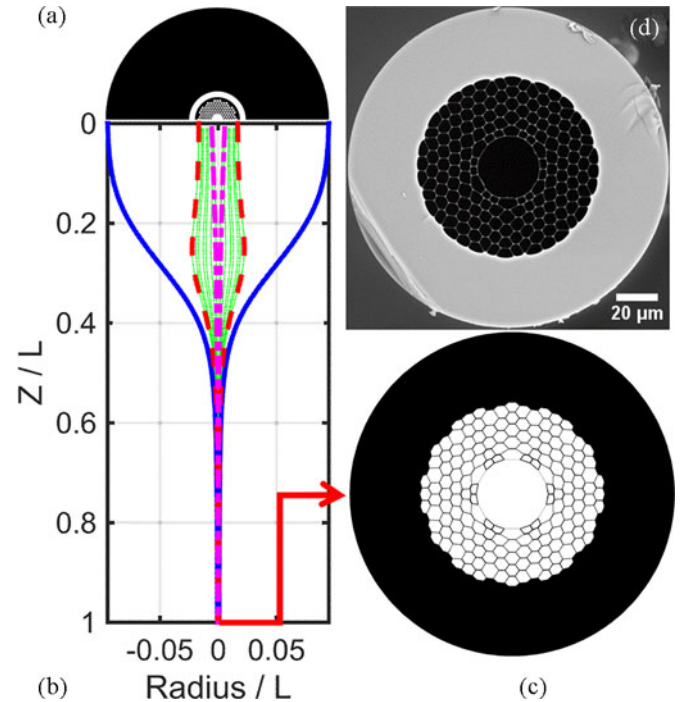

Fig. 3.   (a) Simulated second stage preform; (b) Geometry evolution through the simulated draw-down process; (c) Simulated cross section of the final HC-PBGF; (d) SEM image of the fabricated 1.55 μm fiber.

a 5 cladding ring structure, see Figs. 1(a) and Fig. 3(d), and were fabricated via a two-stage stack-and-draw technique using canes produced from the same primary stack. Through the use of a very thin core tube (supplied by OFS Labs), which allowed us to increase the length of uniform cane produced from the first stage draw, and careful preform design and process control, we successfully scaled up the yield of high quality fiber to the unprecedented lengths of 3.85 km at 2 μm [19] and 11 km at 1.55 μm [20]. In order to minimize the surface mode issues typically associated with the use of an oversized capillary tube to define the hollow core [1], we designed our primary stack to have an optimized ratio between core and cladding strut thickness. To further maximize the transmission BW, we targeted extremely high values of air filling fraction ($\geq$96%) of the cladding.

A. Fabrication of a 3.85 km Long HC-PBGF at 2 μm

We initially targeted the spectral region around 2 μm, which typically involves scaling up the fiber structure as compared

e.g., to HC-PBGFs operating at shorter wavelengths. A scanning electron microscope (SEM) image of the fiber is shown in Fig. 1(a). The fiber has an outer diameter of 195 μm. The microstructured cladding region and hollow core are approximately 109 and 38 μm in diameter, respectively. The average hole-to-hole spacing, Λ, and relative hole size, d/Λ, were estimated to be 7.8 μm and 0.991, respectively.

During the draw, we also monitored in real-time the fiber outer diameter deviation from target in order to gain quantitative information on the stability of the drawing process and thus an indirect indication about the longitudinal uniformity of the fiber. The recorded trace is showed in Fig. 1(b). Over the full length,

the root mean square (RMS) of the diameter deviation is just 0.3 μm ($\approx$0.16% RMS, $\approx$0.6% peak-to-peak), which indicates excellent draw stability.

The length-averaged loss of the fiber was measured by performing a cutback measurement with a broadband source (we made separate measurements using both a supercontinuum laser and an incandescent white light source). A large mode area fiber was used at launch in order to minimize excitation of lossier higher order modes in the HC-PBGF. The spectral attenuation obtained from a $\approx$3.85 km cutback is shown in Fig. 2. From the plot the wide extent of the bandgap ($\approx$1550–2175 nm), which correlates with the high air filling fraction (>96%) of the fiber, is immediately apparent. The bandgap is segmented in three low loss regions as a result of the presence of residual surface modes which we ascribe to small scale deformations and asymmetries in the core surround [21]. The widest of the three regions is centered at about 2050 nm and contains the region of minimum loss, 3.2 dB/km at 1984 nm, and is over 160 nm wide. These loss and BW values are comparable to those reported previously [11], however in a $\approx$3.3$\times$ shorter span of fiber.

Though the relatively low loss value and low value of diameter deviation strongly suggest that the fiber is of consistent high quality over the full length, it would be ideal to get a direct experimental substantiation of this. However, suitable characterization tools, such as Optical Time Domain Reflectometers (OTDRs), are not well developed at the wavelength of 2 μm, so in the next phase of work targeting longer lengths of HC-PBGFs we switched to making fibers operating at the more conventional wavelength of 1.55 μm where a far greater array of diagnostic tools are available.

B. Fabrication of an 11 km Span of HC-PBGF at 1.55 μm

A HC-PBGF operating at $\approx$1.55 μm was obtained by suitably reducing the overall scale of the HC-PBGF whilst targeting a value of air filling fraction similar to that of the 2 μm fiber. In this instance, through further fabrication and control improvements (discussed below), and partly owing to the reduced scale factor of the fiber itself, we obtained an overall yield of uniform fiber in excess of 11 km in a single fiber draw.

The fiber's structural parameters were obtained from high resolution SEM images, where particular care was devoted to minimizing the effect of the gold coating deposited on the samples. The fiber [Fig. 3(d)] has an outer diameter of $\approx$153 μm, $\approx$30 μm core diameter, 6.2 μm hole-to-hole spacing, a relative hole size (d/Λ) of 0.992 and an average cladding strut thickness of just $\approx$50 nm. When considering the fiber length ($\approx$11 km), we believe that some of the glass membranes in the cladding of this fiber have one of the most extreme aspect ratios ever demonstrated in an engineered material. Note that previous reports in the literature of HC-PBGFs fabricated with high values of air filling factor similar to our fiber were characterized by much shorter lengths [22] and/or by high loss [23], [24].

We employed optimization prior to fiber drawing using a novel fluid-dynamic model [18], capable of reproducing the complex HC-PBGF drawing process, Fig. 3(a)–(c), in association with improved control of hole pressurization, in order to
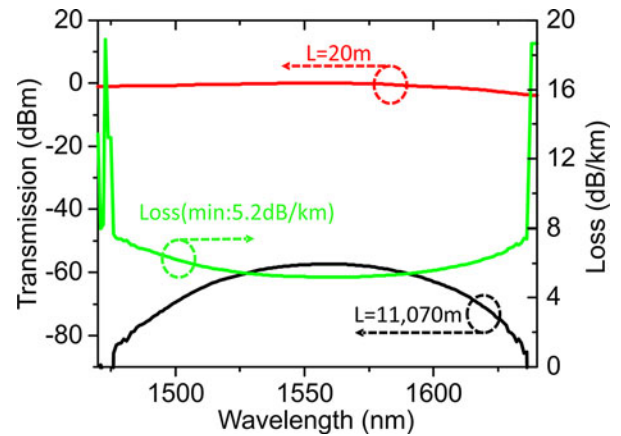

Fig. 4. Spectral attenuation of the full length of the HC-PBGF operating at 1.55 μm (green curve), measured from an 11.05 km cutback, plotted with the associated cutback transmission data.

minimize any distortions of the core surround—a known problem at high expansion values that can lead to increased scattering loss [25] and to instability during the fiber draw.

The spectral attenuation of the fiber was obtained from cutback measurements using the same procedure described above for the 2 μm HC-PBGF and a cutback length of 11.05 km (see Fig. 4). Over the measured wavelength range (1475–1635 nm, limited by OSA dynamic range), the plot shows a very flat loss profile with a minimum value of 5.2 dB/km at 1560 nm. Measurements on a shorter cutback length (0.8 km) provided a value for the 3 dB transmission BW of just over 200 nm, which is to the best of our knowledge the widest ever reported in a 19 cell HC-PBGF. We have experimentally observed the low loss region of transmission to be largely insensitive to bending down to 15–20 mm radii, with some indication of increased loss at the edges likely due to surface mode interaction, similar to what we previously observed [26]. We note that the availability of long lengths of uniform HC-PBGF will enable the more complex characterization of microbending effects in these fibers in due course.

We investigated in detail the longitudinal consistency of this fiber. Fig. 5(a) displays the relative deviation from target diameter, measured as the fiber was drawn, demonstrating a small value ($\approx$0.24 μm, or $\approx$0.15% RMS, $\approx$0.7% peak-to-peak) over the whole 11 km length—similar to that observed for the 2 μm HC-PBGF. We also used a high resolution OTDR to gain information on the longitudinal distribution of the loss along the fiber itself. However, as can be seen form Fig. 5(b), due to its relatively narrow dynamic range (e.g., $\approx$12–13 dB at the maximum spatial resolution of $\approx$0.5–1 m), the OTDR can only provide information from a length up to $\approx$2 km from each end, but is totally unable to probe the central section of the HC-PBGF.

Therefore, we devised a different method to directly characterize the length-resolved transmission loss of our HC-PBGF. It consists of coupling light from an amplified diode laser (1560 nm) into the fiber and measuring the total out-scattered power as the fiber is wound at a constant speed through an integrating sphere fitted with an InGaAs detector—we term this technique Optical Side Scattering Radiometry (OSSR) [27]. In a
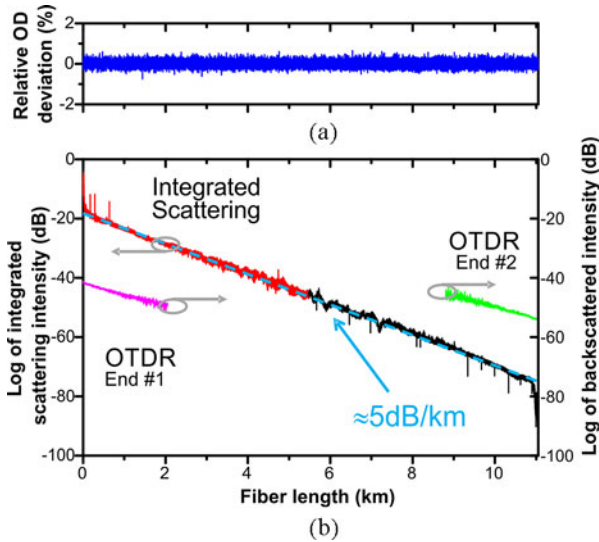
Fig. 5. (a) Diameter deviation versus fiber length measured during fiber drawing; (b) Integrated out-scattered intensity versus length, measured at the wavelength of minimum loss (1560 nm): the red and black traces are measurements obtained from opposite ends of the 11 km span. Note the uniform ≈5 dB/km slope, in excellent agreement with the cutback loss value. OTDR measurements are also shown (pink and green traces, plotted with an arbitrary offset for clarity), highlighting the shorter measurement reach and less accurate loss estimate (≈4 dB/km). Note that the black and green traces are plotted reversed for graphic purposes.

normal scenario, the out-scattered power is observed to decrease at the same rate as the fiber loss. For validation, we measured a sample of Corning SMF-28e fiber and observed a linear slope (in dB scale) matching the loss value specified by the manufacturer. Any deviations from a linear slope indicates some form of longitudinal anomaly of the fiber structure, causing a loss increase (localized or distributed) and/or an increased coupling between the optical modes supported by the fiber.

In our HC-PBGF, we observed the scattered power to decrease at a constant rate of 5.14 dB/km, as shown in Fig. 5(b), in excellent agreement with the length-averaged loss value measured via cutback. To the best of our knowledge this is the first report of a detailed investigation of length dependent loss in a long HC-PBGF sample using an integrated out-scattered power method. The OSSR method provides for a far greater dynamic range (≈60 dB) than OTDR (equating to longer measurable lengths) and it can detect any localized fiber defects with far better spatial resolution (≈10 cm). Furthermore, it can be easily adapted to other wavelength ranges where it may be the easiest option for characterizing the longitudinal properties of fibers. Superimposed on the linear decrease in scattered power, a small number of discrete scattering peaks can be discerned, see red and black traces in Fig. 5(b). We ascribe such peaks to localized small-scale residual inconsistencies within the microstructure. The excess loss due to a single peak can be calculated by integrating the out-scattered power at the defective point and comparing it with that of an adjacent length of structurally consistent fiber. By using this procedure (explained more in detail in reference [27]) we estimated that the peaks account for a comparatively small excess loss contribution (<1 dB out of ≈57 dB
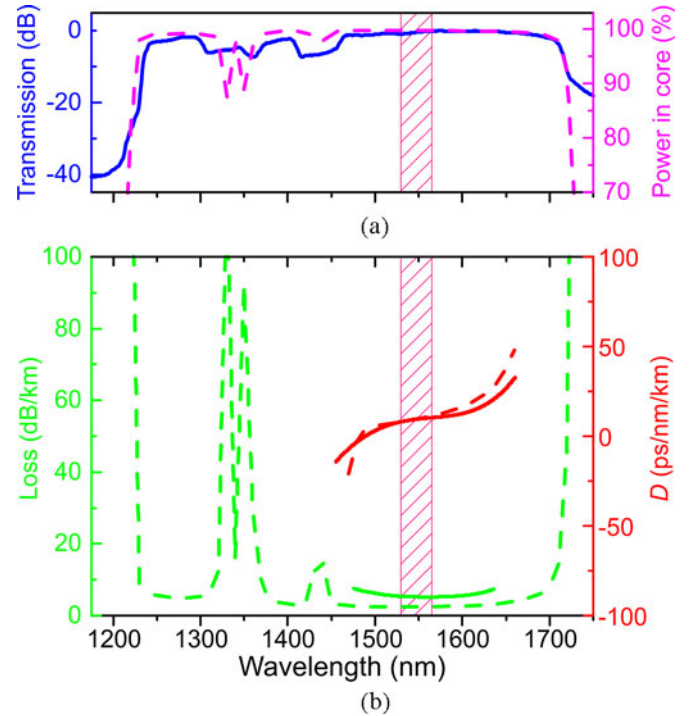

Fig. 6. (a) Comparison of the measured transmission of a 20 m length of HC-PBGF (blue solid curve) with the calculated power in the core (magenta dashed), demonstrating excellent agreement of the position of the bandgap edges and of the surface mode anti-crossings. (b) Measured loss (green solid curve) and GVD (red) versus wavelength and the respective modelled (dashed) curves. The shaded area represents the wavelength range of the telecom C-band at 1.55 μm.

measured for the full fiber length). The integrated out-scattering measurement thus points to a high longitudinal consistency of the 11 km long HC-PBGF.

We also performed finite element simulations based on a model [28] that accurately reproduces the fiber geometry from high resolution SEM images. The model provides predictions for all the main transmission properties of the HC-PBGF, and a comparison with experimental data is shown in Fig. 6(a), (b). We observe that the model can accurately predict the position of the bandgap edges and that of the main surface mode groups within the photonic bandgap, see Fig. 6(a) and green traces in Fig. 6(b). A comparison between the modelled wavelength dependent group velocity dispersion (GVD) of the fundamental mode is also in good agreement with data obtained using low coherence interferometry (red traces). On the other hand, the model predicts a minimum loss value of ≈2.4 dB/km, thus about half of that experimentally measured in our fiber. Given that our scattering measurements indicate that the fiber is structurally very uniform, we conclude that other potential effects are likely responsible for the aforementioned loss discrepancy. These include, but are not limited to, mode coupling, micro bending effects, or a potential surface roughness increase with decreasing thickness of the glass struts. Whilst investigations are ongoing, the current fiber still exhibits an extremely good loss value and there are good prospects for further loss reduction once the cause of the discrepancy is identified and resolved.

TABLE II
SUMMARY OF BEST PERFORMING HC-PBGFS

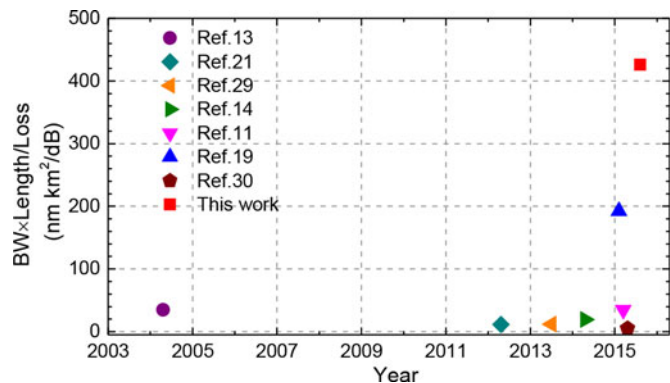| Reference	Year	λ (nm)	Loss (dB/km)	BW (nm)	Length (km)
Mangan *et al.* [13]	2004	1565	1.7	20	Up to 3
Wheeler *et al.* [21]	2012	1510	3.5	160	0.25
Frosz *et al.* [29]	2013	1530	1.8	40	0.5
van Uden *et al.* [14]	2014	1510	8	160	0.95
Zhang *et al.* [11]	2015	1990	2.8	85	1.15
Liu *et al.* [19]	2015	2010	3.2	160	3.85
Mangan *et al.* [30]	2015	1538	6.5	12	2.75
This work	**2015**	**1560**	**5.2**	**200**	**11.07**

Fig. 7. Best performing HCPBGFs reported to date (summarized in the table) are compared via a *length* × BW/loss figure of merit to visualize recent improvements.

C. Performance Improvement and Comparison With the SOTA

Table II presents a summary of the best performing HC-PBGFs previously reported by groups worldwide, which are compared in terms of minimum loss, transmission BW and fabricated length to those discussed in the present study. In Fig. 7 we also plot the quantity *length* × BW/loss as a figure of merit providing a visual indication of how the different fibers compare and a temporal perspective of the most recent advances obtained particularly in increasing the BW and the fiber length. The 11 km long HC-PBGF presented in this work provides a ≈20% increase in BW and at least a ≈4 × increase in length as compared to the previous SOTA. Our models based on realistic fiber structures indicate that further significant loss reduction (substantially below 1 dB/km) should be possible [1]; furthermore, recent results obtained from a fluid dynamic model of the fiber drawing process confidently predict that it should be possible to scale up current fabrication to multi-hundred km lengths [17].

IV. DATA TRANSMISSION EXPERIMENTS

We were able to demonstrate that both the fibers reported in this work were able to support error-free data transmission. In particular, use of the 3.85 km long span of 2 μm HC-PBGF was demonstrated for single channel transmission at 52 Gbit/s. A detailed description of this experiment has recently been published elsewhere [19]. In this section, we will focus on the results obtained using the 11 km long span of 1.55 μm HC-PBGF.
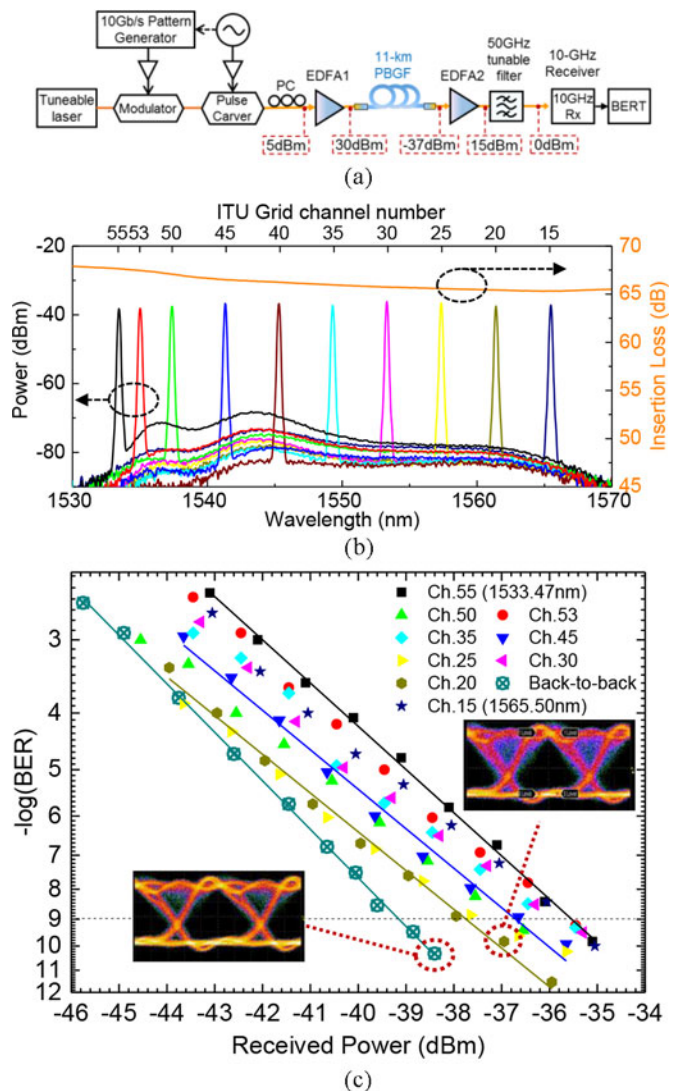

Fig. 8. (a) Experimental RZ-OOK data transmission setup; (b) Channels transmitted through the 11 km HC-PBGF (0.1 nm resolution); (c) BER measurements for back-to-back and various transmitted channels, and corresponding eye diagrams for back-to-back and channel 20.

As shown in Fig. 6, the width of the low loss region of the HC-PBGF (≈200 nm) significantly exceeds that of the telecom C-band. Thus, our demonstration was limited by the BW of the available optical amplifiers. The total insertion loss of the HC-PBGF span, including splice loss from interconnections to SMF 28 (and associated mode mismatch loss) was a substantial 66–67 dB. Such a high span loss required amplification of the signal to ≈30 dBm prior to the transmission. Whilst use of such high power levels could cause serious drawbacks in long spans of conventional SMF, it was not expected to cause any penalty in the HC-PBGF due to the ultra-low nonlinearity of the HC-PBGF. We successfully tested both coherent transmission (QPSK) and direct detection using OOK.

We first show the results of direct detection as it allows for the lowest transmission latency, thus underlining this key feature of HC-PBGFs. Further, we used a return-to-zero modulation format as it allowed for better performance. The received signal
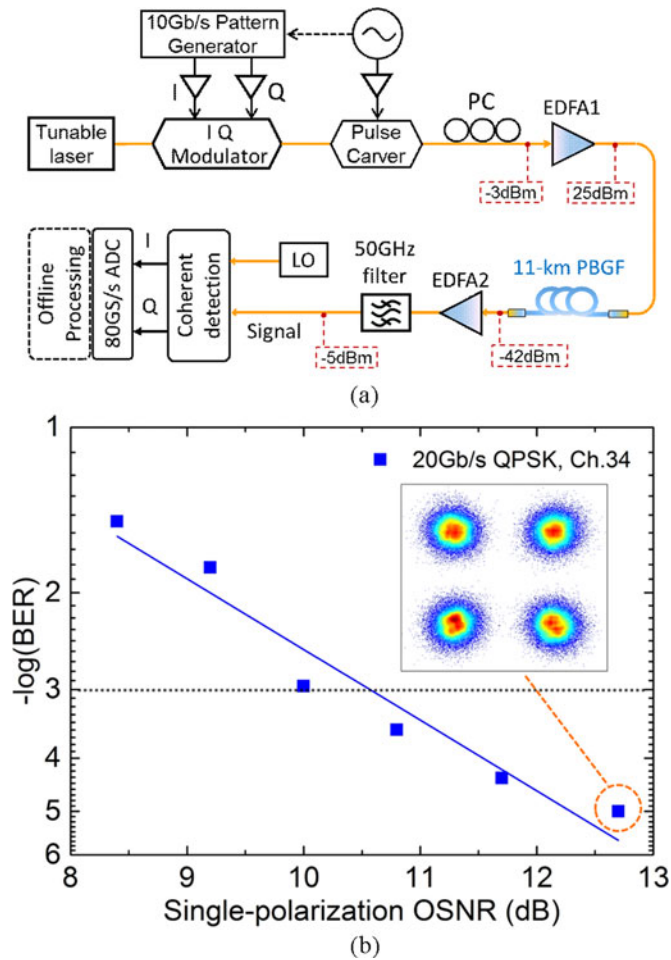
Fig. 9. (a) Experimental RZ-QPSK data coherent transmission setup; (b) BER measurements for the transmitted signal on channel 34 (1550.12 nm), and the constellation diagram of the demodulated signal at OSNR of 12.7 dB.

(≈ -37 dBm) was optically pre-amplified, filtered and detected with a 10-Gbit/s receiver, see Fig. 8(a). The optical spectra of several tested C-band channels (15 to 55) measured at the HC-PBGF output end are shown in Fig. 8(b). Here, we notice that the optical signal-to-noise ratio (OSNR) in the region of 1537–1565 nm is almost constant and over 40 dB. For wavelengths at the edges of the EDFA's gain BW (1532–1537 nm, 1565–1568 nm), the OSNR and thus the transmission performance were slightly degraded due to ASE (Amplified Spontaneous Emission) from the input EDFA.

The Bit Error Ratio (BER) measurements are shown in Fig. 8(c). Wavelength channels in the flat-gain region have a BER performance close to that of the back-to-back (penalty ≤ 2 dB). A penalty of up to 4 dB was measured for the transmission channels at the edges of the EDFA gain profile, which we believe is entirely due to the worse OSNR. Thus, we conclude that the fiber provides a similar performance across the entire C-band with a few dB variation that is attributed to the fiber loss rather than any other effect (e.g., signal degradation due to modal crosstalk).

In addition to the direct detection experiment, we also tested the HC-PBGF using 20 Gb/s QPSK coherent transmission as

shown in Fig. 9(a). The experimental setup is similar to the direct detection experiment except for the use of an IQ modulator for QPSK generation and a coherent receiver with 80 GSa/s analog-to-digital convertor for reception. The electronic data source used was a dual-channel arbitrary waveform generator (AWG, Tektronix AWG7122C) operating at 10 GSa/s.

The BER as a function of single-polarization OSNR for channel 34 (1550.12 nm) is shown in Fig. 9(b). Error free transmission was achieved by launching >25 dBm power into the HC-PBGF (5 dB lower than that used for direct detection), which corresponded to a >13 dB OSNR after the receiver-side pre-amplifier. The linear relationship of OSNR and –log(BER) confirms that the performance was limited by the fiber loss as was for the previously discussed direct detection experiment.

V. CONCLUSIONS

We have presented two record length HC-PBGFs operating in the 1.55 and 2 μm spectral regions, respectively. Both fibers have loss of the order of a few dB/km and very broad transmission bandwidths. The HC-PBGF operating at 2 μm is 3.85 km long and has ≈ 3 dB/km minimum loss and over 160 nm 3 dB transmission BW. Furthermore, a fiber operating at standard telecom wavelengths (1.55 μm) was obtained in an unprecedented length of 11 km. The length-averaged fiber loss, measured over the full 11 km span, was ≈ 5 dB/km and the 3 dB transmission BW was found to be about 200 nm – a further improvement over HC-PBGFs previously reported at this wavelength. An integrated side scattering technique was applied to measure the longitudinal distribution of the loss along the full fiber length, providing a first insight into the properties of such a long span of HC-PBGF and convincing evidence of its excellent uniformity and structural consistency. Data transmission at 10 Gb/s (direct detection) and 20 Gbit/s (coherent detection) along an 11 km span was demonstrated for the latter fiber, showing only penalties due to the fiber loss and achieving an estimated >15 μs latency reduction relative to standard fiber.

The availability of long lengths of high performance HC-PBGF with uniform transmission characteristics opens up the possibility of application trials of realistic scale. Furthermore, our numerical models of the fiber draw process give us confidence that much longer fiber yield per preform should be possible with further scaling of the process [17], and that much lower loss fibers should ultimately be possible.

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