# Demonstration of an 11km Hollow Core Photonic Bandgap Fiber for Broadband Low-latency Data Transmission

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**Abstract:** We report the fabrication of a record 11km length of photonic bandgap fiber supporting >200nm bandwidth with longitudinally uniform loss of ≈5dB/km at 1560nm and demonstrate error-free, low-latency, direct-detection 10Gbit/s transmission across the entire C-Band.

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## 1. Introduction

Recent years have seen a resurgent interest in hollow core photonic bandgap fibers (HC-PBGFs) [1]. The primary driver for this is the potential for low-latency, guided-wave data transmission which is of great interest for several time-sensitive application areas, including: intra and inter data center interconnection, high performance computing, large-scale high energy physics experiments, and bespoke data networks for the financial sector. Whilst impressive progress has been made and the key enabling properties of HC-PBGFs, e.g. low latency [2], low nonlinearity [3], the ability to support broad-bandwidth high capacity transmission on the fundamental [4] as well as on multiple optical modes [5] have reliably been confirmed, demonstrations to date have used samples of relatively modest (<≈1km) lengths. This has primarily been due to the difficulties in scaling up the HC-PBGF fabrication procedures [1], the elimination of defects/contamination that can occur during preform manufacture [6], and the lack of means to ensure that a sufficient structural uniformity is maintained along the full fiber draw. Until it can be demonstrated that long lengths of HC-PBGF can be reliably fabricated and such samples become available to test in application trials of realistic scale, industrial/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 recently developed by our group, we report a significant step forward in HC-PBGF technology – the fabrication of what we believe to be the first high performance HC-PBGF with a length in excess of 10km, providing a combination of bandwidth (>200nm) and loss (≈5dB/km) that is close to the current state-of-the-art for much shorter fiber lengths. Furthermore, we demonstrate the viability of 10Gbit/s RZ-OOK data transmission over a HC-PBGF span of 11km, a length compatible with many of the applications listed above. The reduction in propagation latency as compared to a similar length of SMF is confidently estimated to be >15μs. Furthermore, our numerical models of the fiber drawing process give us confidence that much longer fiber yields are feasible through further scaling of the process [7], and that much lower loss fibers should ultimately be possible.

## 2. Fabrication and characterization of record long HC-PBGF

The HC-PBGF has a 19 cell core and 5 cladding ring structure (see Fig. 1d) and was fabricated via a two-stage stack-and-draw technique. Use of a very thin core tube (supplied by OFS Labs) allowed us to increase the length of uniform cane produced and through careful preform design and process control we successfully scaled up the yield to an unprecedented >11km length of high quality fiber. We designed our stack to have an optimized ratio between core and cladding strut thickness, thus minimizing any potential surface mode issues associated with the use of a core tube [1]. To further maximize the transmission bandwidth, we targeted extremely high values of air filling factor (>96%) of the cladding. The fiber has ≈30μm core diameter, 6.2μm hole-to-hole spacing, a relative hole size (d/Λ) of 0.992 and average cladding strut thickness of just ≈50nm (measured from SEM images). Note that previous reports of similarly extreme structures were characterized by high loss [8, 9], and/or shorter lengths [10]. We employed optimization prior to fiber drawing using a novel fluid-dynamic model [11], capable of reproducing the complex HC-PBGF drawing process, Fig. 1a-c, in association with improved control of hole pressurization, in order to minimize any distortions of the core surround – a known problem at high expansion values that can lead to increased scattering loss [12] and to instability during the fiber draw. The transmission loss (Fig. 1e), obtained via a cutback measurement (11.05km) using a supercontinuum source, shows a minimum value of 5.2dB/km (1560nm) and a very flat profile over the measured range (1475-1635nm, limited by OSA dynamic range). Finite element simulations based on a model [13] that accurately reproduces the fiber geometry from high resolution SEM images predicts a 3dB bandwidth in excess of 200nm (fundamental mode), and this value was experimentally confirmed from a shorter 800m cutback. As demonstrated in Fig. 1e, the model accurately predicts the position of the bandgap edges, that of the main surface mode groups within the photonic bandgap and the dispersion (data obtained using low coherence interferometry for the fundamental mode also shown in Fig. 1e). The minimum loss predicted by our model is ≈2.4dB/km, which prompted an investigation into the longitudinal consistency of the fiber.

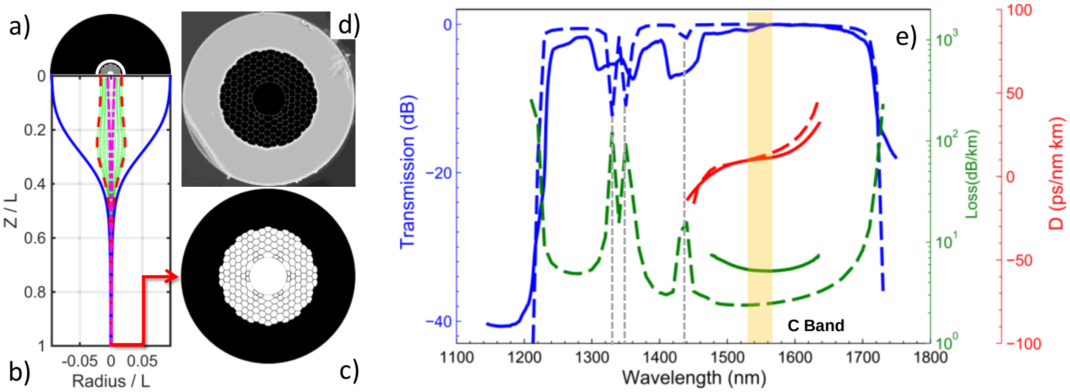
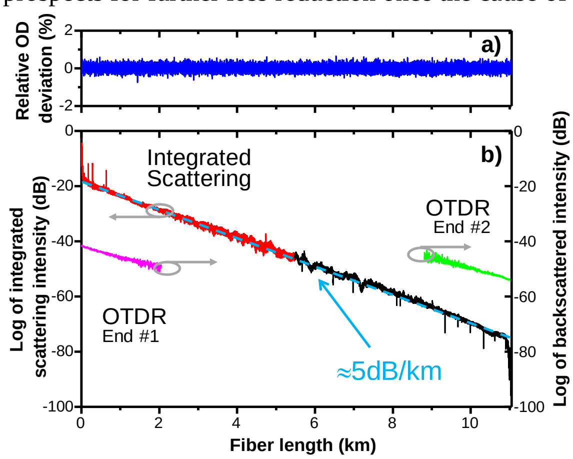
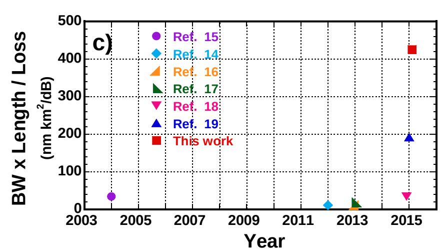



Fig. 1: (a) Simulated second stage preform; (b) Geometry evolution through the simulated draw-down process; (c) Simulated cross section of final HC-PBGF; (d) SEM image of fabricated fiber; (e) Measured loss (green solid curve) and dispersion (red) and the respective modelled (dashed) curves; plot also shows a comparison of the measured transmission of a 20m length of HC-PBGF (blue solid curve) with the calculated power in the core (blue dashed), demonstrating excellent agreement of the position of the bandgap edges and of the surface mode resonances.

Fig. 2a displays the relative deviation from target diameter, measured as the fiber was drawn, demonstrating a small value (≈0.15% RMS, ≈0.7% peak-to-peak) over the whole 11km length. We further confirmed the structural consistency by coupling a 1560nm diode laser into the fiber and measuring the total out-scattered power via an integrating sphere fitted with an InGaAs detector as the fiber was spooled at a constant speed. The scattered power decreased at a constant rate of ≈5dB/km, as shown in Fig. 2b, in very good 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 such a method, which provides far greater dynamic range than OTDR (equating to longer measurable lengths) and can detect any localized fiber defects with far better resolution (≈10cm). A small number of discrete peaks can be discerned, which we ascribe to localized small-scale residual inconsistencies within the microstructure. We estimated these peaks account for no more than 1dB excess loss over the full fiber length. These measurements point to high longitudinal fiber consistency and indicate that other potential effects are 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 still 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.




| Reference | λ (nm) | Loss (dB/km) | BW (nm) | Length (km) |
|---|---|---|---|---|
| Mangan et al. [15] | 1565 | 1.7 | 20 | Up to 3 |
| Wheeler et al. [14] | 1510 | 3.5 | 160 | 0.25 |
| Frosz et al. [16] | 1530 | 1.8 | 40 | 0.5 |
| van Uden et al. [17] | 1510 | 8 | 160 | 0.95 |
| Zhang et al. [18] | 1990 | 2.8 | 85 | 1.15 |
| Liu et al [19] | 2010 | 3.2 | 160 | 3.85 |
| This work | 1560 | 5.2 | 200 | 11.07 |

Fig. 2: (a) Diameter deviation vs. fiber length drawn; (b) Integrated out-scattered intensity vs. length (1560nm): the red and black traces are measurements obtained from opposite ends of the 11km span. Note the uniform ≈5dB/km slope, in excellent agreement with the cutback loss value. OTDR measurements are also shown (pink and green traces, plotted with an arbitrary offset), highlighting the shorter measurement reach and less accurate loss estimate (≈4dB/km). Note that the black and green traces are reversed for graphic purposes; (c) Best performing HC-PBGFs reported to date (summarized in the table) are compared via a *length*×BW/loss figure of merit to visualize recent improvements.

The table in Fig. 2 summarizes the best performing HC-PBGFs previously reported by groups worldwide. In Fig. 2c we plot the quantity *length*×BW/loss as a figure of merit providing a visual indication of how the different fibers compare in terms of length, transmission bandwidth and loss. The HC-PBGF in this work provides a ≈20% increase in BW over the previous SOTA and a ≈3× increase in length as compared to our recent result [19].

## 3. Data transmission Experiments

As the width of the low loss region of the HC-PBGF significantly exceeds the telecom C-band, our demonstration was limited by the amplifier bandwidth. The total insertion loss of ≈66dB (including splice loss from inter-connections to SMF-28) required amplification of the signal to ≈30dBm prior to the transmission. Use of such high power levels was not expected to cause any penalty due to the ultra-low nonlinearity of the HC-PBGF. We successfully tested both coherent transmission (QPSK) and direct detection using OOK. Although the low received power favors the use of coherent detection, here we 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 (≈-37dBm) was optically pre-amplified, filtered and detected with a 10Gbit/s receiver, Fig. 3a. The optical spectra of various C-band channels (15 to 55) measured at the HC-PBGF output end are shown in Fig. 3b. Here, we notice that the optical signal-to-noise ratio (OSNR) in the region of 1537-1565nm is almost constant and over 40dB. For shorter wavelengths (1532-1537nm), the OSNR and thus the transmission performance were slightly degraded due to ASE from the input EDFA. BER performance is shown in Fig. 3c. Longer wavelength channels have BER performance close to that of the b-2-b (penalty ≤2dB). A penalty of up to 4dB was measured for the short wavelength channels, 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 penalty that is attributed to the fiber loss rather than any other effect (e.g. signal degradation due to modal crosstalk).

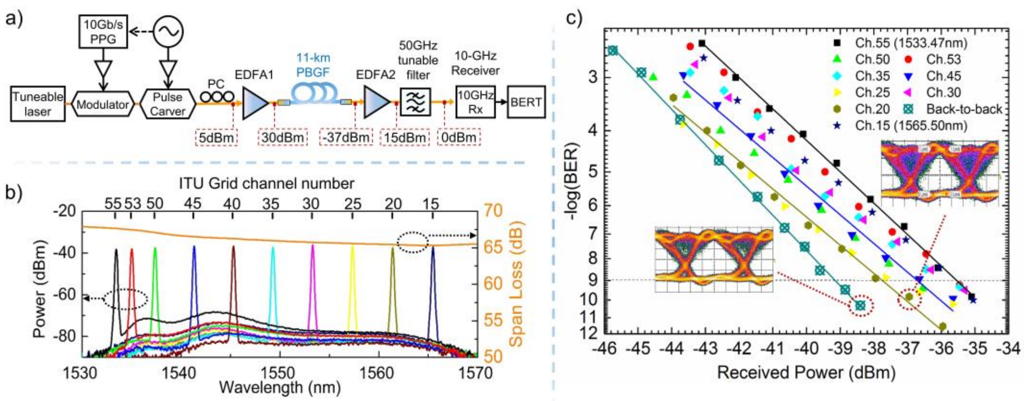



Fig. 3: (a) Experimental RZ-OOK data transmission setup; (b) Channels transmitted through the 11km HC-PBGF (0.1nm resolution); (c) BER measurements for back-to-back and various transmitted channels, and corresponding eye diagrams for back-to-back and channel 20.

## 4. Conclusions

We have presented an 11km long HC-PBGF characterized by ≈5dB/km loss and a very broad transmission bandwidth. The length dependent loss was investigated via a side scattering technique, providing for the first time an insight into the properties of such a long span of HC-PBGF and on its structural consistency. Data transmission at 10Gb/s along a 11km span was demonstrated using direct detection, showing only minor penalties and achieving an estimated >15µs latency reduction relative to standard fiber. This first ever report of a >10km length of high performance HC-PBGF opens up the possibility of application trials of realistic scale.

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