Photonic bandgap fibres for low-latency data transmission

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Abstract: *We review progress in the design, fabrication and characterisation of hollow core photonic band gap fibres that have led to the production of low-latency data transmission fibres of >10 km length with 200nm bandwidth and losses at the 5dB/km level.*

Introduction

Renewed interest has developed over recent years in the use of hollow-core photonic bandgap fibres (HC-PBGFs) for applications in communications. The primary reasons for this lie in their potential for low loss (ultimately potentially down to values lower than that of conventional solid SMF (albeit at wavelengths around 2000nm)), their ultralow nonlinearity (since the signals propagate predominantly in air), and the low-latency guided-wave data transmission they enable (again since the signals propagate in air) [1]. Low latency in HC-PBGFs is of great interest for various time-sensitive applications, including: intra and inter data centre interconnection, high performance computing and for bespoke networks serving, for example, the financial sector [2]. Whilst the potential of the technology has been demonstrated in various system experiments these have generally been on fibres of ~1km length due the challenges of making long structurally uniform lengths of fibre [3-6]. Until much longer samples become available to test in application trials of realistic scale, industrial/commercial interest in the technology will obviously remain limited.

In this paper we review our recent advances in the fabrication of long lengths of HC-PBGF with characteristics close to, or beyond in some parameters, the current state of the art. These advances have been enabled by the development of various new numerical design, fabrication and characterization tools and have now resulted in production of the first HC-PBGF sample with a length >10km. The fibre has already been successfully used in low latency transmission experiments [7].

Fabrication and characterization advances

HC-PBGFs are generally fabricated using a two stage stack and draw method [1]. In order to make long lengths of fibre it is essential to ensure a highly uniform second stage preform with carefully matched microstructured cane and cladding tube dimensions, accurate and reliable pressurisation of the preform and excellent diameter stability throughout the fibre draw. It is also critical to ensure a high degree of cleanliness throughout the fabrication process as any inadvertent inclusion of contaminants can lead to localised defects causing excess fibre loss and potentially fibre breaks. It is also critically important to understand in detail how preform structure evolves and distorts during the fibre draw process due to fluid dynamics so that the preform needed to obtain a given target fibre structure can be designed (the fibre structure has to be carefully engineered to avoid the presence of surface modes and to obtain both a broad operating bandwidth and low loss [8,9]). To this end we have developed non-destructive tools to: assess the structure and consistency of preforms [10] and the presence and nature of defects within the final fibre (so that these can be eliminated through improved processes) [10,11]; numerical models of the fluid-dynamics of the fibre drawing process [12]; methods to allow rapid real time assessment of fibre structure [13]; and tools to accurately predict the optical performance of fibres from structural images [14].

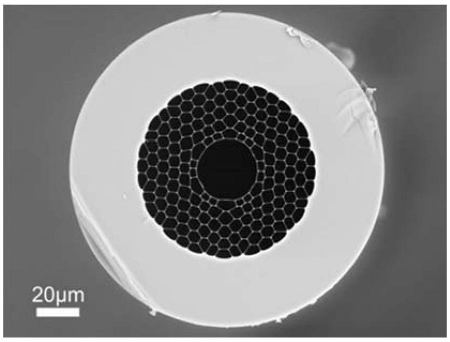

Fig. 1 Cross-sectional SEM image of the 19-cell HC-PBGF.

By applying all of these tools we were able to realise our 11km HC-PBGF fibre. The HC-PBGF has a 19 cell core and a 5 cladding ring structure (see Fig. 1a). We used a very thin core tube (supplied by OFS Labs, USA) to allow us to increase the length of uniform cane produced in the first stage draw and scaled up the yield of the second stage draw to an unprecedented >11km length of high quality fibre. We designed our initial 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. To further maximize the transmission bandwidth, we targeted extremely high values of air filling factor (>96%) of the cladding. The fibre has a ~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 high resolution SEM images). Note that previous reports of similarly extreme structures were characterized by high loss [15, 16], and/or shorter lengths [8].

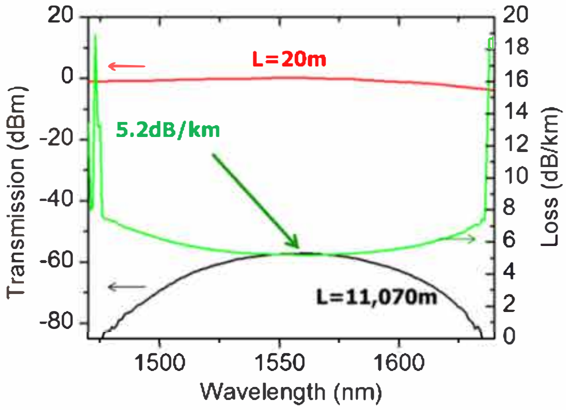

Fig. 2 Spectral transmission (green curve) over the full 11km fibre length along with the associated cut-back data.

The transmission loss (Fig. 2), obtained via a cutback measurement (11.05km) using a supercontinuum source, shows a minimum value of 5.2dB/km (1560nm) with a very flat profile over the measured range (1475-1635nm, limited by OSA dynamic range). Simulations from high resolution SEM images predicted a 3dB bandwidth in excess of 200nm – a value confirmed by cutback measurements from a shorter 800m length (which had lesser dynamic range requirements).

To illustrate the uniformity of the fibre we display the relative deviation from target diameter, measured during the fibre draw, which shows ~0.15% RMS, ~0.7% peak-to-peak deviation over the full 11km length in Fig. 3a. We further confirmed the longitudinal consistency of the fibre by coupling light from a 1560nm diode laser into the fibre and measuring the total out-scattered power along the length by spooling it at constant speed through an integrating sphere fitted with an InGaAs detector. The scattered power decreased at a constant rate of ~5dB/km, as shown in Fig. 3b, in very good agreement with the length-averaged loss value measured via cutback.

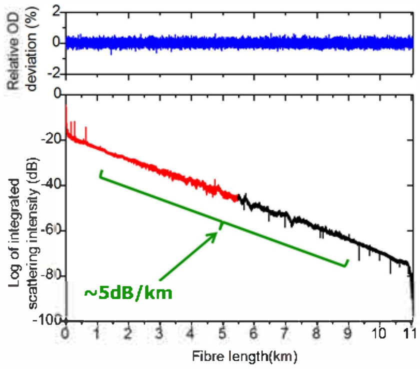

Fig. 3 (a) Relative deviation from target diameter, measured as the fibre was drawn illustrating~0.15% RMS deviation over the whole 11km length. (b) Outscattered power as a function of fiber length indicating a relatively uniform loss of ~5dB/km.

Low Latency Transmission Experiment

We connectorised the PBGF with SMF pigtails (loss ~4 dB per-pigtail due to the significant mode-mismatch between the fibres (this could be significantly improved with the availability of a suitable buffer fiber with an optimised intermediate core dimension)), obtaining a fully connectorised sample with a total insertion loss of ≈66dB. In order to facilitate transmission we amplified the signal to ≈30dBm prior to launch into the sample - use of such a high power level is acceptable due to the ultra-low nonlinearity of the HC-PBGF. We successfully tested both coherent transmission (20 Gbit/s QPSK) and direct detection (10 Gbit/s) using a low latency compatible OOK signal format. The received signal (≈-37dBm) was optically pre-amplified, filtered and finally detected with a 10Gbit/s receiver.

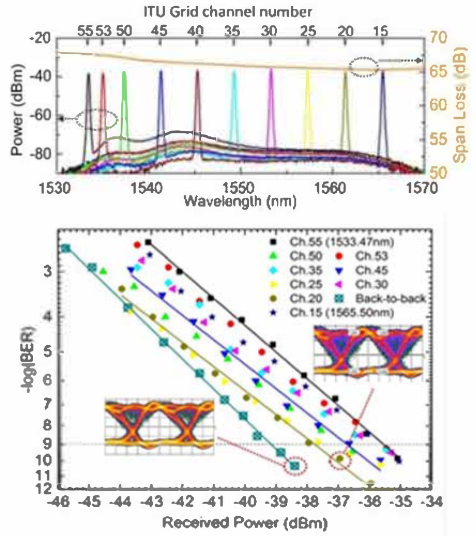

Fig.4 (a) Channels transmitted through the 11km HC-PBGF (0.1nm resolution); (b) OOK BER measurements for the back-to-back and various transmitted channels, and corresponding eye diagrams for the back-to-back and channel 20.

The optical spectra of various C-band channels (15 to 55) measured at the HC-PBGF output are shown in Fig. 4a. We note that the optical signal-to-noise ratio (OSNR) was >40 dB and almost constant over the range 1537-1565nm. For shorter wavelengths (1532-1537nm), the OSNR and thus the overall transmission performance were slightly degraded due to higher levels of ASE from the input EDFA. The corresponding BER performance for the 10 Gbit/s OOK modulation format signal is shown in Fig. 4b. The longer wavelength channels show a 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 to be entirely due to the degraded OSNR. Thus, we conclude that the fibre provides similar performance across the entire C-band with a few dB penalty that can be attributed to noise generated inside the fibre amplifiers used (two amplifiers with total gain > 70 dB) rather than any other effect (e.g. signal degradation due to modal crosstalk).

Conclusions

In summary we have described the development and transmission performance of a record 11km length of HC-PBGF. The fibre has 5dB/km loss and a very broad transmission bandwidth, representing a very significant improvement over the previous state of the art. Data transmission at 10Gb/s along the full 11km fibre length without any observable error floor (down to the 10^{-12} BER level) has been demonstrated using direct detection, showing only minor penalties and enabling an estimated >15μs latency reduction relative to the use of a similar physical length of standard fibre. Whilst these results are significant in themselves and bring a number of important applications into range, our (well calibrated) optical and fluid dynamic simulations lead us anticipate significant further reductions in loss (to well below 1 dB/km) [1,9], and the possibility to make significantly longer lengths of fibre per draw [17].

Acknowledgements

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