Record Low-Loss 1.3dB/km Data Transmitting Antiresonant Hollow Core Fibre

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Abstract *We report fabrication of a Nested Antiresonant Nodeless hollow-core Fibre (NANF) with a minimum loss of 1.3dB/km at 1450nm and a 65nm bandwidth below 1.5dB/km. The 0.5-km long fibre is effectively single moded and is shown capable of data transmission.*

Introduction

Hollow core fibres (HCFs), where glass in the core is replaced by a gas or vacuum, have attracted the attention of scientists worldwide for over a century due to their ultralow nonlinear response, fast propagation speed and the potential for a propagation loss below that of conventional fibres. Despite advances in many of their optical properties that make them appealing for numerous applications[1-2], their use in optical communications is still severely limited by the current levels of optical loss. The lowest rigorously documented loss in a HCF is 1.7 dB/km and was obtained in a photonic bandgap guiding HCF (PBGF)[3]. Its low loss transmission bandwidth was ~20 nm, limited at both spectral passband edges by surface modes, which are known to make such fibres susceptible to perturbations. No data transmission was ever reported through this fibre. A subsequent publication mentioned that a 1.2 dB/km fibre with similar structure had been achieved, however it did not include any data about the spectral dependence of the loss/bandwidth, length, or structure[4]. In recent years, the difficulty of further reducing the loss in these fibres has meant that the research community has shifted its focus towards antiresonant hollow core fibres (ARFs), in which guidance is based on antiresonant reflections from membranes surrounding the core. Thanks to a 10-100x lower fraction of power in the glass than in PBGFs, ARFs have already exceeded the performance of PBGFs in many areas, and have now become the fibre of choice for power delivery applications and to deliver light at wavelengths where the glass is lossier[5,6]. Recently, we have shown that an ARF made by longitudinal capillaries attached only to the inside of a jacket tube is also capable of transmitting data[7]. Its air-guiding bandwidth was over 1000 nm in a single window and its loss ~25 dB/km. Similar fibres with <8 dB/km[8] have since been reported, an impressive loss level, but still too high for most data transmission applications

It is now well known, that by adding a set of smaller nested tubes the loss of the fibre can theoretically be considerably reduced[9]. Various groups have reported good progress towards the realisation of such a Nested Antiresonant Nodeless Fibre (NANF), but all have so far failed to achieve the required structure/symmetry necessary for low loss[10,11]. Recently, a significant step towards the demonstration of a low loss ARF was reported using a modification of the NANF concept, where additional radial double reflections were obtained by inserting glass sheets in the stack[12]. The length and minimum reported loss were 330 m and 2.0 dB/km respectively, but the presence of nodes in the microstructure around the core caused significant spectral oscillations due to glass/air mode interactions. The data transmission performance of the fibre was seemingly not tested.

Here we report a 0.5 km NANF with the lowest documented loss for any type of HCF (1.3 dB/km at 1450 nm) and show that it supports effectively single mode guidance after a suitable propagation length and good data transmission.

Fabrication and Characterisation

The fabricated NANF has 6 nested tubes surrounding a 31 µm core and a length of 505 m. Its cross section, OTDR and an image of the output spatial mode profile are shown in Fig. 1.

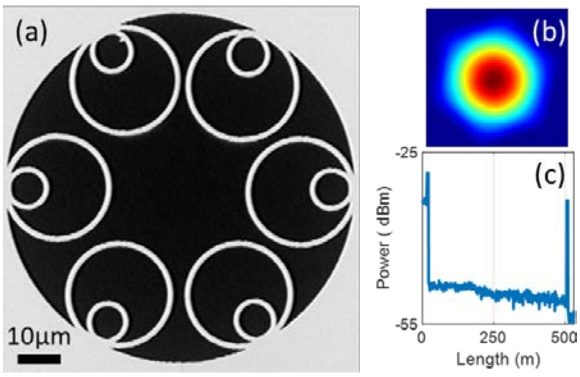

Fig. 1: (a) SEM; (b) mode at fibre output; (c) OTDR trace of the fabricated fibre

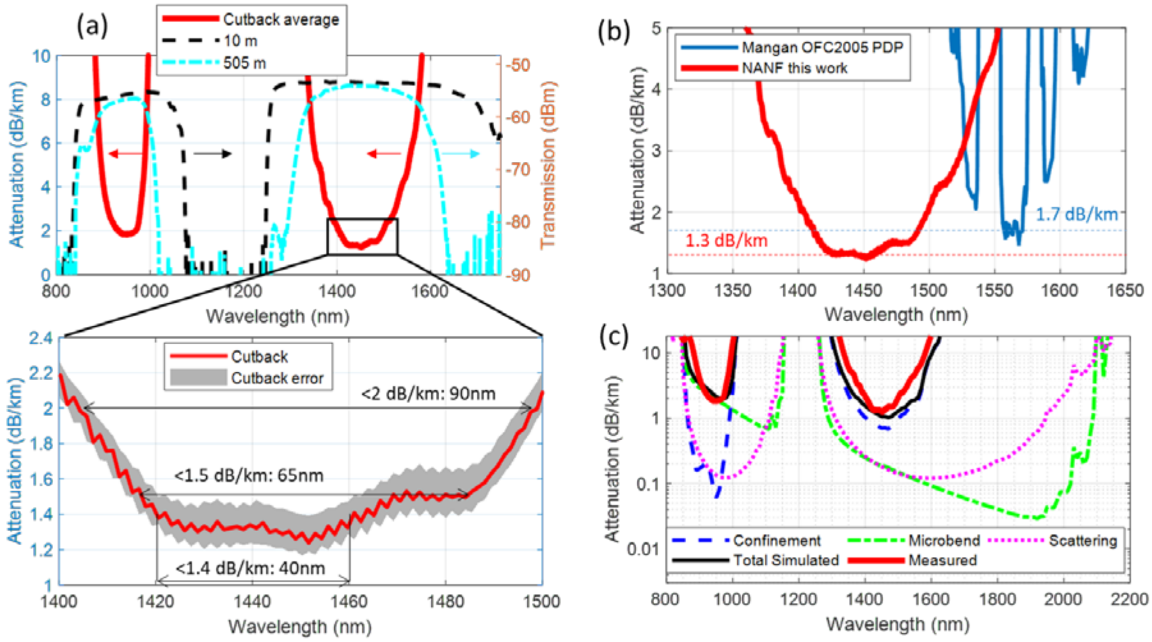

Fig. 2: (a) (Top) Transmission through long and short fibre lengths and average cutback loss, (Bottom) zoomed in cutback with measurement error (shaded area); (b) comparison between present fibre loss and previous HCF loss record in ref [3]; (c) Total simulated loss (black) vs measurement (red) and various loss contributions: confinement (blue dash), scattering (red dot); microbend (green, dash-dot).

It was fabricated by stacking and fusing inside a jacket tube a set of capillaries of very similar aspect ratio as in the final fibre but ~200 times bigger, followed by a conventional two-stage draw approach. The inner and outer set of tubes were held at a different pressures in the fibre draw stage to realise similar wall thicknesses. The selection of pressures was assisted by fluid dynamics modelling[13]. The thickness of the six outer tubes is 1170±29 nm, chosen to provide C-band operation in the second antiresonant window. Second window operation allows two times thicker membranes than for the first window, and thus a more controllable fabrication process providing an easier target for this initial demonstration. As a downside, the bandwidth is 3-4 times narrower than e.g. ref [7] and the yield is reduced. The fibre draw was very stable and controllable, and remarkably small inter-tube azimuthal gaps down to ~1 wavelength could be achieved and maintained along the full fibre length. The small remaining azimuthal asymmetries and the fact that the inner tubes are slightly thinner than the outers (1080±25 nm) provides scope for improvement in future draws.

The fibre was then spooled on a 1-m circumference bobbin and cut back to 10 m. Its spectral transmission curves and cutback loss are shown in Fig.2a. OSA measurements were acquired (for three different cleaves) at both long and short fibre lengths. The red solid line indicates the average loss and the grey shaded area around it the measurement error. The minimum loss region falls short of the C-band (something that can be straightforwardly addressed in future draws), and is centered around 1450 nm. The minimum, average and maximum loss around 1450 nm are 1.2, 1.3 and 1.4 dB/km, respectively. The fibre has a loss below 1.4 dB/km over a bandwidth of 40 nm, <1.5 dB/km over 65 nm and <2 dB/km over 90 nm. Fig. 2b shows how its second transmission window loss compares with the previous HCF record loss in ref. [3].

The measurement is further supported by simulations, as shown in Fig. 2c. Image processing was used to extract accurate structural information from SEMs, and mass conservation from the preform was imposed to improve accuracy in estimating individual tube thicknesses. Three loss contributions were evaluated: *confinement* from FEM calculations; *surface scattering* using the model in ref. [9]; and *microbend* from the coupled power theory model in ref. [15], using an experimentally measured spectral dependence of the external perturbation. As can be seen, by summing up all contributions, excellent agreement is observed not only for the 2nd window around 1450 nm, but also for the 3rd window around 950 nm. At 950 nm the minimum loss of 1.8 dB/km is also a record value and only 2x higher than Rayleigh scattering in silica. The observation that confinement and microbend dominate the loss in the 2nd and 3rd window respectively, can drive future improvements.

The low values of scattering loss, a contribution that dominates loss in PBGFs, stems from the fact that in NANFs all glass membranes

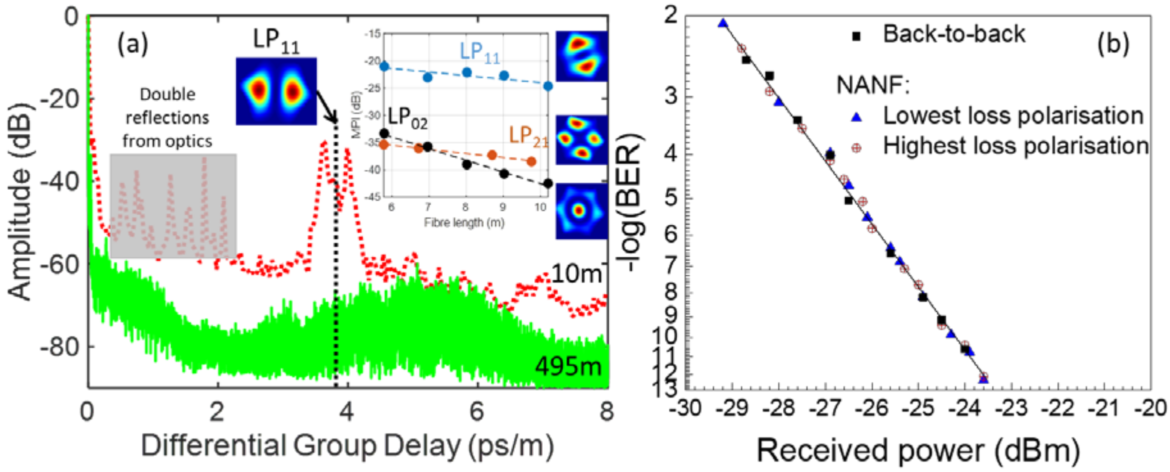

Fig. 3: (a) S^2 measurement after 10 m (red) and 495 m (green); in the inset: S^2 cutback on 10m of fibre using a purposely offset launch; (b) BER measurement, 10Gbit/s, single channel at 1550nm through a fully connectorised 495m of fibre.

operate in antiresonance, and the fraction of power in the glass is extremely low (estimated to be 0.016% for this fibre). This also generates ultra-low values of intermodal coupling, which combined with a large loss for all high order modes due to a mode-stripping geometric effect[9] gives the fibre excellent modal properties. An experimental S^2 cutback indicates losses of LP_{11}, LP_{21} and LP_{02} modes as high as ~640, 750 and 2100 dB/km respectively, while S^2 after 0.5 km showed no evidence of the LP_{11} mode (Fig. 3a).

To test the data transmission capability of the fibre, we spliced the spooled fibre to SMF at both ends and connected it to a commercial 10G SPF+ 80-km reach transceiver. The operating wavelength was 1550 nm, where the loss of the fibre was 4.7 dB/km. The total insertion loss at 1450 and 1550nm were 1.9 dB and 3.5 dB (1.25 dB additional loss from two pairs of splices and connectors). A PDL of 1-dB was measured on the fully connectorised fibre, however no BER power penalty was observed when aligning the input polarization to the axes of minimum or maximum loss (Fig 3b). A Bit Error Ratio (BER) of 10^{-9} was achieved for a received power of -24.6 dBm. The fibre was then left under test for over 60 hours at a received power of -20 dBm and no errors were detected. This indicates the absence of an error floor at the 10^{-15} BER level and confirms the expected low levels of intermodal coupling and multi-path interference. Whilst more systematic tests will need to be performed in due time, previous high capacity transmission results on a non-nested ARF[16] give confidence that the present fibre should exhibit excellent high capacity data transmission performance.

Conclusions

We have reported the first data-transmitting NANF. To the best of our knowledge, the fibre has the lowest documented loss for an HCF of any type - 1.3 dB/km at 1450nm and 1.8 dB/km at 950 nm. Its wide bandwidth, high intermodal differential loss and low intermodal coupling are most promising attributes for future demonstrations of high capacity transmission. Although the fabricated length is short and the minimum loss is not yet centered on the C-band, we believe that this result represents a key first milestone in the practical development of a new fibre technology, NANFs, with great potential for further performance enhancement. Simulations, that have been shown to accurately reproduce the current results, predict that by moving to the 1st window and by enlarging the core to 40 µm (both of which seem technically achievable) the bandwidth should more than double and the loss decrease by a factor of ~10 (see ref. 9).

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