Bend Insensitive Hollow Core DNANF with SMF-Matching Mode Field Diameter and 125µm Outer Diameter for Low Loss Direct Interconnection in Short Reach Applications

Ghafour Amouzad Mahdiraji, Jaroslaw Rzegocki, Ian A. Davidson, Gianluca Guerra, Gregory T. Jasion, Seyed Mohammad Abokhamis Mousavi, Yongmin Jung, Austin Taranta, Kyle Bottrill, Periklis Petropoulos and Francesco Poletti*

Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK,
**Also with Microsoft Azure Fiber, Romsey, United Kingdom: fp@soton.ac.uk*

Abstract: We present the first 125µm outer diameter hollow-core fibre with a 10.6µm mode-field diameter allowing direct low-loss splicing to G652 SMF. We demonstrate O-to-C-band transmission and bend-insensitive single-mode operation, attractive for low-latency sub-1km communications.

1. Introduction

Hollow core optical fibres (HCFs) offer near vacuum and temperature-stable latency, negligible nonlinearity, and low dispersion across a spectral window as wide as several hundred nanometres, due to a low glass-light overlap.

HCFs can also achieve a propagation loss comparable to (or potentially better than) standard single mode, step-index fibres (SMFs), if their geometry is optimised to minimise the sum of all the attenuation-inducing mechanisms (leakage, surface scattering, macro and micro bend losses) [1]. An example of such optimisation can be seen in the HCF with the lowest loss reported so far (0.174 dB/km at 1550 nm) [2]. This was a Double Nested Antiresonant Nodeless Fibre (DNANF) with 5 sets of double-nested tubes. Minimizing its loss required scaling the core diameter to 28 µm, corresponding to a mode field diameter (MFD) of ~70% of this number [3], or 19.6 µm. This is nearly twice the 10.4 µm MFD of a standard G652 SMF at 1550 nm, requiring some form of mode-field adaptation to interconnect the two fibres with low loss and low intermodal interference. The larger MFD of the HCF also makes it intrinsically more sensitive to macro and micro bend loss. The former prevents tight coiling or sharp bends, while the latter requires a stiffer glass jacket, typically 1.5-2x thicker than the 125 µm standard diameter of SMFs.

As the HCF performance improves and its penetration into data and laser transmission markets increases, ecosystems will likely form for fibre diameters larger than 125 µm and with non-standard MFDs. But, for the time being, interconnection with SMF is still required for most applications. Good performance splicing [4] and gluing [5] of SMF-HCF, mediated by intermediate buffer fibres, can be achieved, not only in the lab but also during cable installations in the field. However, there is no doubt that if HCFs could be made with an improved geometrical match to SMFs that does not require special handling, the usability of the technology would be dramatically improved. This comes at the cost of some inevitable increase in loss, the amount of which has never been estimated nor demonstrated.

In this work, we present the first HCF with both MFD (~10.6 µm) and outer diameter (125 µm) matched to SMF. We show that its optical properties in the O, E, S and C bands are suitable for single-mode short-reach optical communication. The fibre also offers record-low bend loss performance and record-low loss at 600-800 nm.

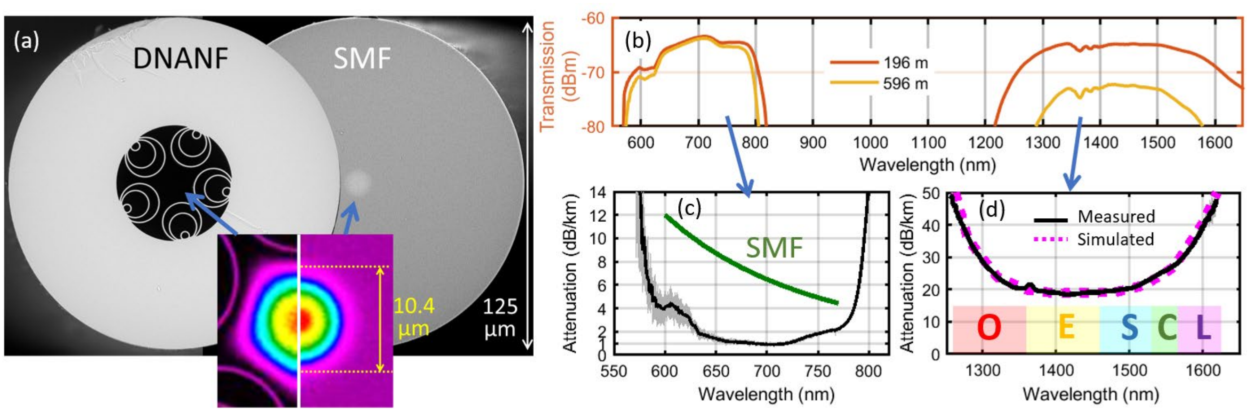

Fig.1 (a) Microscope image of the fabricated DNANF and its measured optical mode, compared with G652 SMF; (b) Broadband fibre transmission at 10 nm resolution. Cutback loss measurement: (c) in the 2nd antiresonant window, compared with a commercial single mode fibre (Thorlabs 630HP [7]), and (d) in the 1st antiresonant window, compared with the total simulated loss.

2. Fibre Design

In principle, HCFs guiding through photonic bandgaps could be produced with an SMF-matching MFD. However, fibres with a 7-cell core design tend to guide >10 air modes with similar loss, and hence suffer from intermodal interference, while the single mode 3-cell core version has MFDs intrinsically much smaller than 10.4 μm [6]. Therefore, here, we focus on antiresonant HCFs, where the core diameter D_c can be chosen arbitrarily. Due to its effectiveness in reducing leakage loss, we chose a DNANF structure [2]. To match its MFD to that of SMF requires D_c as small as 14.5 μm. As D_c reduces, the leakage and surface scattering loss increase, while macro and micro bend losses decrease. Theory predicts that for antiresonant fibres like DNANFs, leakage loss should increase approximately like D_c^{-10} [1], reaching ~120 dB/km and becoming the dominant loss mechanism. However, with thorough structural optimisations using an FEM numerical solver, we identified a DNANF design with a loss as low as ~20 dB/km at 1550 nm, adequate for short reach links.

3. Fibre fabrication and characterisation

A small core DNANF with 5 nested tube sets and a design close to the optimum was fabricated. Fig.1(a) shows the cross-section of the fabricated fibre, compared to that of an SMF. The fibre's outer glass and inner microstructure diameters are 125 and 43.5 μm, respectively. The core is 14.5 μm, while the average inter-tube gap and membrane thickness of the three nested tubes are 2.4 μm and ~515 nm, respectively. The draw was stable, yielding multiple bands that included the 596 m we report here. For this, the end-to-end core size variation is only 0.2 μm.

The loss of the fibre was measured via a cutback from 596 to 196 m (Fig.1b), using a white light tungsten halogen source and a spliced launch. The fibre shows two transmission windows: 1300-1600 nm, and a second window at 580-800 nm (Fig.1c), where it achieves a loss of 4.0, 1.4, 0.9 and 1.8 dB/km at 600, 650, 700 and 750 nm, respectively. Note that despite the small D_c, in this spectral region this is the lowest loss ever reported in an HCF, and it is considerably lower than the typical loss of a commercial SMF (e.g. Thorlabs 630HP [7], shown in green in Fig.1c). This makes it attractive for laser delivery in biomedical work, and for the transmission of quantum states and entangled photons in quantum computing, networking and memories, e.g., based on Praseodymium (606 nm), Thulium (793 nm), Rubidium (780 nm) ion traps, or on NV centres in diamond (637 nm).

In the fundamental window (Fig.1d) the fibre was designed to guide all wavelengths from the O to the L band. Its loss reaches a minimum of 18 dB/km at 1410 nm, and it increases to ~26 dB/km at both 1310 and 1550 nm. This is in excellent agreement with the simulated loss of this structure (pink curve). Simulations also show that reducing the core from 28 to 14.5 μm, increases the light-glass overlap (from $\sim 6\text{x}10^{-5}$ [2] to $\sim 6\text{x}10^{-4}$), but the fibre retains a negligible nonlinearity and a near-vacuum latency. Likewise, the simulated chromatic dispersion (not shown) has also increased and behaves similarly to SMF, crossing zero at 1310 nm and increasing to 14 ps/nm/km at 1550 nm.

The bend loss of this fibre at 1550 nm, simulated (brown line) and measured (red crosses), is compared with that of solid core fibres, Fig.2a. Not only is this HCF less bend sensitive than SMF (G652), but at bend radii <15 mm it is also significantly less bend sensitive than trench-assisted G657 (A1, A2 and B3) designs [8].

To assess the modal quality, a 17.5 m long fibre was directly spliced to a launch SMF patchcord and its high-order mode content measured through S^2 [9], Fig.2b. Shortening the fibre to 5 m in 2.5 m intervals with three cleaves per length, produced an estimated LP11 mode loss of 1.4 dB/m (Fig.2c), matching the simulated 1.4 dB/m and guaranteeing single mode operation (5 m from the splice the LP11 mode is ~ -37 dB below the LP01).

The air mode's near field has a Gaussian-like profile in the centre, with a 5-fold symmetry at the edges and a measured $1/e^2$ MFD of 10.6 μm; close to SMF's 10.4 μm giving a butt coupling loss between this DNANF and SMF of 0.4 dB. Of this, 0.18 dB is attributable to Fresnel reflection and minimizable with A/R coating. The remaining 0.22 dB (5%) is partly caused by the mode shape mismatch and partly by small residual size mismatch. When

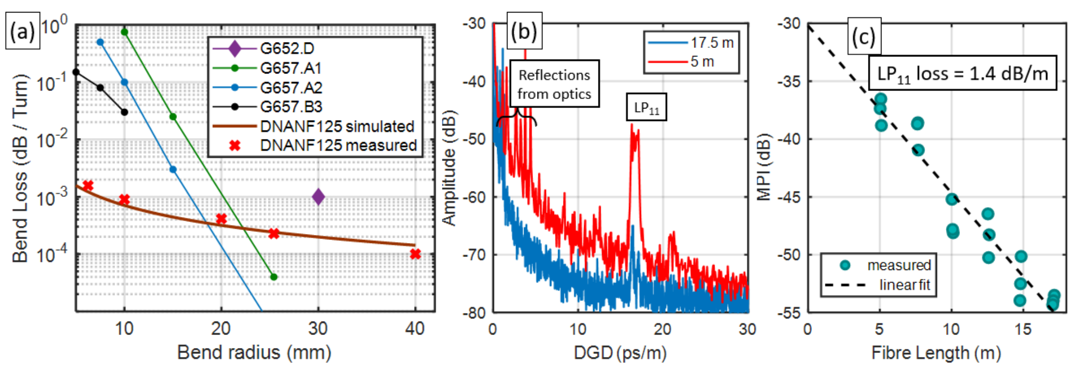

Fig.2 (a) Bend loss of the fabricated DNANF (simulated and measured), compared to G652 and various bend insensitive G657 solid core SMF specifications; (b) S^2 measurement at 17.5 m and 5 m lengths; (c) LP_{11} loss determined from S^2 cutback from 17.5 to 5 m at 2.5 m intervals.

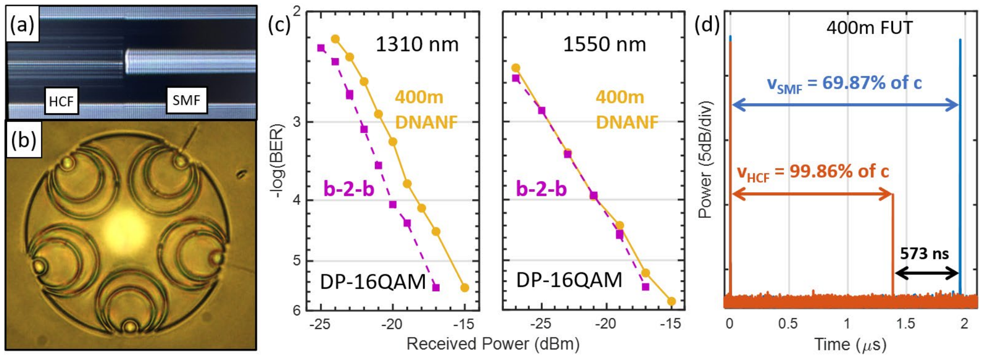

Fig.3 (a) HCF-SMF spliced using cladding alignment (Fujikura FSM100); (b) microstructure imprint on SMF due to splicing, showing no structural deformation. (c) BER data taken back-to-back (b-2-b) and after transmission of DP-16QAM at 1310nm and 1550nm; (d) Short-pulse time of flight measurement comparing 400m of HCF with an identical length of Corning SMF-28e.

splicing in a standard Fujikura splicer (Fig.3a), additional loss in the range 0.01-0.1 dB was observed over 10 splices (total splice loss: 0.41-0.5 dB). Breaking the splice (Fig.3b) reveals a strong fusion with minimum deformation.

To validate the short-reach data transmission capability of the fibre, we spliced 400 m of this DNANF to SMF at both ends (total splice + fibre loss: 11.2 dB). Due to the absence of nonlinear effects in these HCFs, we limited the test to a single channel per band. The BER curves of a DP-16 QAM transmission at 22.5 GBaud can be seen in Fig.3c. At 1550 nm no power penalty is observed, while ~1.5 dB was measured at 1310 nm. This is still under investigation, but it is anyway small enough to confirm the modelling prediction that the fibre behaves essentially as single moded across the 1310-1550 nm region. Finally, we have demonstrated a 30% reduction in latency versus an identical length of SMF or a saving of 143 ns every 100 m (Fig.3d).

4. Discussion and Conclusions

We have shown for the first time that a practical HCF, of DNANF type, can be produced with optical and geometrical properties compatible with SMF. The 125 µm outer diameter of this HCF allows compatibility with standard fibre cleaving, splicing, and cabling tools, significantly improving the useability of the technology. The fibre can be spliced to SMF with a loss of 0.41 dB without any intermediate mode field matching fibre. When launching light from a solid spliced patchcord, the HCF is essentially single moded. Besides, at very small bend radii it presents 10-100x lower bend loss than the best trench assisted G657-B3 (e.g. ~0.001 dB/turn at 13 mm bend diameter), making it ideal for use where tight bending or coiling is required. In the second window around 600-800 nm, the fibre has the lowest loss ever reported for an optical fibre, 2-9 times lower than commercial SMF. Here, it could be transformative for the transmission of single photons or entangled states. In the fundamental window, the small core diameter of 14.5 µm increases the leakage-dominated loss by ~150x over a 28 µm core counterpart [2], reaching 20-46 dB/km in the O-band, 23-28 dB/km in the C-band and 26 dB/km at both 1310 nm and 1550 nm. While clearly high, this loss level is acceptable for low latency (temperature-stable [10]) laser and data transmission over distances below a few hundred metres, e.g. in 5G front-haul, high performance computing or intra-datacentre interconnections. Finally, modelling predicts that with modest design changes it should be possible to reduce the loss to ~5 dB/km, further increasing the appeal of this small core DNANF technology.

Acknowledgements

Research partly sponsored by EPSRC Airguide Photonics (EP/P030181/1).

References

[1] E. N. Fokoua, et al., "Loss in hollow-core optical fibers: mechanisms, scaling rules, and limits," *Adv Opt and Photon* 15, 1-85 (2023),
[2] G. T. Jasion, et al, "0.174 dB/km Hollow Core Double Nested Antiresonant Nodeless Fiber (DNANF)," *OFC* (2022)
[3] V. Zuba, et al., "Limits of Coupling Efficiency into Hollow-core Antiresonant Fibres," *J. Lightwave Tech.* 41, no. 19, pp. 6374-6382 (2023)
[4] C. Wang, et al., "Ultralow-loss fusion splicing between antiresonant hollow-core fibers and antireflection-coated single-mode fibers with low return loss," *Opt Letts* 48, 1120-1123 (2023)
[5] D. Suslov, et al., "Low loss and high performance interconnection between standard single-mode fiber and antiresonant hollow-core fiber". *Scientific Reports* 11, 8799 (2021)
[6] M. N. Petrovich, et al., "Robustly single mode hollow core photonic bandgap fiber," *Optics Express* 16, 4337–4346 (2008)
[7] Thorlabs product information, "630HP - Single Mode Optical Fiber, 600 - 770 nm, Ø125 µm Cladding", https://www.thorlabs.com/thorproduct.cfm?partnumber=630HP , accessed 15 September 2023.
[8] International Telecommunications Union, "G.657 : Characteristics of a bending-loss insensitive single-mode optical fibre and cable", https://www.itu.int/rec/T-REC-G.657-201611-I/en , accessed 15 September 2023.
[9] J. W. Nicholson, et al., "Spatially and spectrally resolved imaging of modal content in large-mode-area fibers", *Optics Express* 16, no. 10, 7233-7243, (2008)
[10] Z. Feng, et al., "Hollow-core fiber with stable propagation delay between −150°C and +60°C", *Opt Letts* 48, 763-766 (2023)