First Triple Nested Antiresonant Nodeless Hollow Core Fiber (TNANF) Achieving 0.25 dB/km Loss with Small 145/250 µm Glass/Coating Diameters

Ghafour Amouzad Mahdiraji[1], Gregory Jackson[2], Seyed Mohammad Abokhamis Mousavi[1], Naveen Krishna Baddela[2], Jaroslaw Rzegocki[2], Gianluca Guerra[2], Mahmudur Rahman[2], Chiang Ping Saw[2], Ian A. Davidson[2], Gregory T. Jasion[2], Austin Taranta[2], and Francesco Poletti[1,2*]

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

Abstract *We report an improved antiresonant hollow-core fibre with triple-nested tubes to minimise loss at SMF-type 250µm coating diameters. When MFD-matched to SMF, the fibre has 0.54 dB/km and record bend-loss performance. Increasing its MFD by ~30% produces 0.25 and 0.35dB/km at 1550 and 1310nm, respectively. © 2025 The Authors*

Introduction

Hollow core fibres (HCFs), particularly those exploiting antiresonant guidance, have emerged as a transformative platform for optical communications, offering a unique combination of low latency, minimal nonlinearities, and reduced thermal sensitivity compared to conventional all-glass single-mode fibres (SMFs). These advantages stem from the guidance of light predominantly in air [1]. By changing designs and finely engineering the structures, loss in these fibres has dropped by more than 100x in the last decade (Fig. 1).

Recently, a HCF with a record-low attenuation of 0.091 dB/km and more than twice the bandwidth of standard SMF was reported [2]. Achieving such ultralow loss, however, typically requires large cores and mode field diameters (MFDs) — often twice those of SMFs — which in turn necessitate increased outer fibre dimensions and stiffness to mitigate microbend-induced losses. Fibres with up to 240 and 480 µm glass and coating diameters respectively have been reported recently [3]. While acceptable for many applications, these larger diameters pose challenges when high-density cables are required to reduce deployment costs.

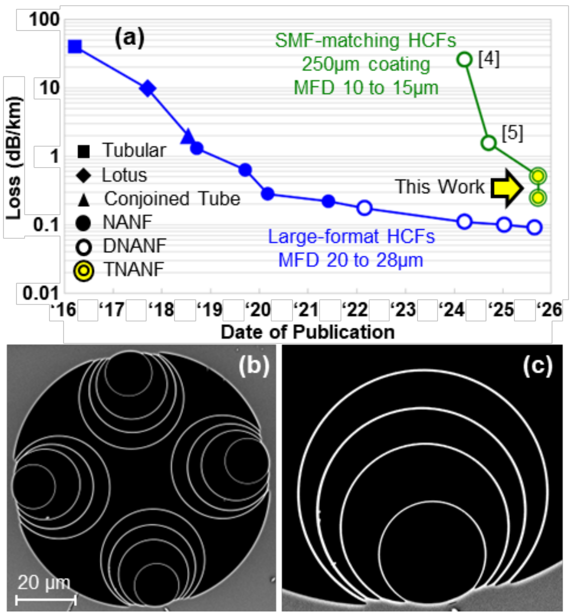

Fig.1: (a) Progress of antiresonant HCF loss in the range 1450-1650 nm for small and large core/cladding sizes, (b) SEM of a fabricated TNANF, (c) closeup of triple nested element.

To address this, a focused research effort has started exploring the performance limits of HCFs constrained to the standard 250 µm outer coating diameter of SMFs. Two years ago, we reported the first SMF-compatible Double Nested Antiresonant Nodeless Fibre (DNANF), featuring five nested tube units and exhibiting a loss of ~20 dB/km [4]. Last year, we improved upon this by reducing the structure to four nested tubes, achieving a significantly lower loss of ~2 dB/km—approaching the theoretical limit for that geometry due to confinement loss [5].

In this work, we present the world's first Triple Nested Antiresonant Nodeless Fibre (TNANF), designed to further suppress confinement loss through the introduction of an additional nested glass tube in the cladding, Fig.1(b). We report two fibres, both with an outer coated diameter of 250 µm. The first has a 15 µm core diameter and an MFD well matched to SMF, achieving a loss of 0.54 dB/km at 1550 nm. The second, with a larger 20 µm core and a 30% increased MFD, demonstrates a record-low loss for an SMF-sized HCF of only 0.25 dB/km in the C-band.

These results mark a significant step toward the realisation of low-loss, SMF-compatible HCFs suitable for high-density optical cable deployments, bringing the latency and nonlinearity benefits of HCFs to high-capacity communication and datacentre interconnection (DCI) networks.

Modelling and Fabrication

Improving compatibility between HCFs and the existing SMF ecosystem requires fibres with a 250 µm coating package and a small core size to enable simple interconnection. Reducing the core size has the undesirable effect of increasing confinement and scattering losses. On the other hand, this reduces macrobend loss, for bend robustness, as well as microbend loss, enabling the use of smaller glass and coating package diameter. The first generation of this fibre approach [4] had a loss of ~20 dB/km. Simulation indicated that 96% of that was confinement loss. The second version improved total loss by ~10x, but confinement loss still comprised 80% of the total loss, with scattering making up the remainder.

Therefore, in this work we have developed a new design which further reduces confinement loss, through the use of four triple nested capillary units. Two versions of this design have been explored: TNANF A has a 15 μm core and an MFD close to SMF. TNANF B has larger core, bringing an increase in coupling loss to SMF (~0.6 dB for a Gaussian mode approximation), but indicated by modelling as the optimum size to minimise the overall fibre loss (Fig.2(a)). These designs were explored numerically and optimal parameters identified for membrane thicknesses, and the size of each of the 16 capillaries. TNANF A has an outer glass diameter of 125 μm to match SMF, while TNANF B has a glass diameter of 145 μm; both have a total coated diameter of 250 μm to match SMF. Simulation of the fabricated cross-sections (dotted lines in Fig.2(b)) corresponding to Fibre A and B should theoretically produce a loss of 0.5 and 0.2 dB/km at 1550 nm, respectively. Importantly, in both fibres the confinement loss contribution is reduced to 52% and 21%, respectively, confirming that the triple nested tubes are effective. The scattering loss determines the lowest loss achievable for a given core size.

The preform was made from Heraeus F300 fused silica glass via the stack and draw method. During the fibre draw we used inline monitoring [6], fluid dynamics modelling [7] and multi-zone pressurisation to achieve the optimised fibre structures. The two fibres presented were originally 370 and 1800 m in length, and were drawn from two similar preforms, both of which had the potential to realise >5km of fibre.

TNANF A, Fig.2(c) has a core diameter of 14.8 ±0.1 μm. The microstructure capillary diameters are nominally 25.3, 19.8, 15.2, and 8.7 μm, all deviating less than 0.5 μm azimuthally. The fibre shows good longitudinal stability, with capillary diameters changing by at most 0.3 μm over the length. Average capillary thicknesses for TNANF A was 480 nm. A critical parameter for confinement loss is the gap between adjacent capillary groups; this fibre has an average gap of 3.2 μm.

TNANF B, Fig.2(e) has a core diameter of 19.5 μm and 20.9 μm at the start/end of the band. The average microstructure capillary diameters are 32.5, 27.2, 22.1, and 13.4 μm, all deviating less than 0.5 μm azimuthally. The average thickness of these capillaries is 430 nm. This fibre shows more drift along the length of the fibre with the average capillary diameter decreasing in size by 1.5, 1.1, 1.0, and 1.5 μm, respectively. Consequently, the gaps between adjacent capillaries increases from an average of 4 μm to 5.5 μm.

The coated fibre cross sections of TNANF A and B are compared to SMF-28 in Fig.2(c-e). Fig. 2 (f,g) show the sideview image of the two TNANFs when spliced to SMF.

Characterisation

The loss of both fibres was measured via cutback

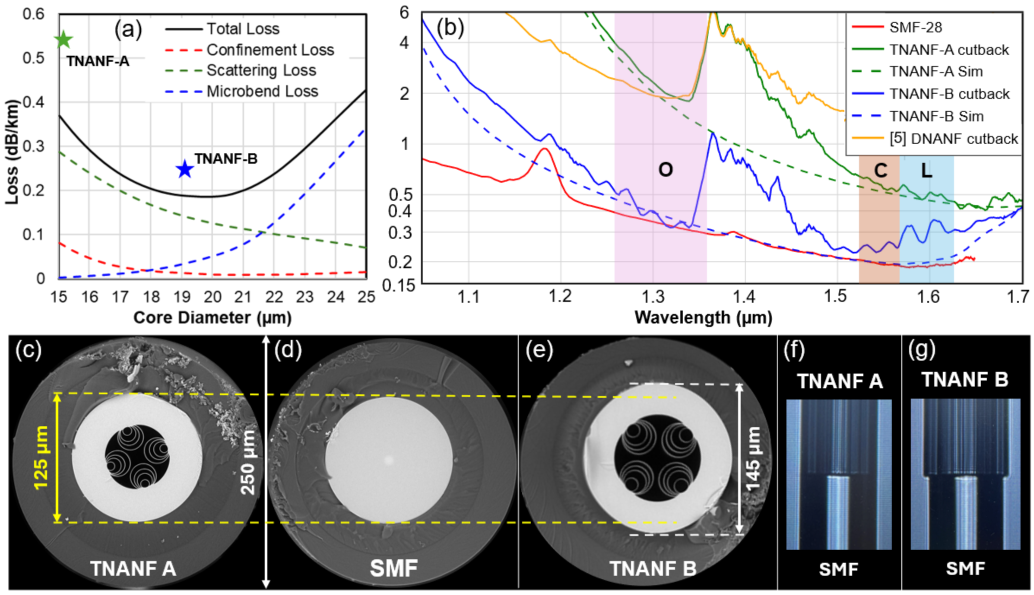

Fig.2: (a) Modelling results showing loss contributions versus TNANF core size, (b) Cutback and modelling results for the two TNANFs presented here, compared to our previous DNANF and to SMF-28. Visual comparison of: (d) TNANF A, (e) SMF-28 and, (f) TNANF B, all imaged with their dual coatings. Splicer images of (g) TNANF A-SMF and, (h) TNANF B-SMF.

with a direct splice to an SMF launch fibre connected to a white light Halogen source (Bentham WLS100) and the spectrum measured by a Yokogawa AQ6374 OSA. At each length, spectra were taken 3 times and averaged, with the output recleaved between each measurement. TNANF A was cutback from 370 m to 20 m, and TNANF B was cutback from 1800 m to 750 m. The results are shown in Fig.2(b), together with their total simulated loss. These loss curves are also compared with the loss of the previous best SMF-matched DNANF [5], and with an SMF-28 measured using the same cutback method. TNANF A has a loss of 0.54 ± 0.08 dB/km at 1550nm, with a minimum loss of 0.4 dB/km at 1660nm, <0.63 dB/km loss across the entire C and L band, and <1 dB/km from 1480 to 1720 nm. The larger core TNANF B shows a loss of 0.25 ± 0.02 dB/km from 1500 to 1550 nm, and over 250 nm of bandwidth (including S, C, L and most of the O band) below 0.4 dB/km. The loss at 1310 nm is 0.35 dB/km. Removing the water vapour absorption peak at 1350-1450 nm would result in a ~400 nm bandwidth with <0.4 dB/km.

The bend loss of both fibres was measured. We tested 2.5 m of TNANF A, wound to radii of less than 10 mm. In Fig.3(a) the result is compared to the performance of G652 and G657 SMFs. The small core size of TNANF A and its multiple antiresonant tubes give it remarkable bend tolerance, superior to G657.B3. To the best of our knowledge, this is the most bend tolerant fibre guiding at 1550 nm ever reported. Due to its larger core size, TNANF B showed a relatively higher bend loss, but still of the order of 0.02 and 0.001 dB/turn at 50 and 80 mm bend radius, respectively, which makes it readily useable even in intra-datacentre deployments.

To find the modal content of these TNANFs we conducted S2 cutback measurements. A length of 100 m was measured using an S2 to find the power and DGD of the higher order modes. The fibre was then cutback 3 times by 25 m without disturbing the launch, and the modal content measured for each length. The LP11 was the only mode found to be prominent, and its power is plotted vs fibre length in Fig.3(b). TNANF A was found to support the LP11 with a loss of 91 dB/km, while the larger core TNANF B has a similar LP11 loss of 95 dB/km. This equates to an LP11/LP01 loss ratio of 190 and 380 respectively. Whilst the fibres are not strictly single mode, a central launch from a spliced SMF, limited coupling mechanisms and high differential loss between the two guided modes make them in practice effectively single mode.

By measuring TNANF coupling loss to SMF we can assess another aspect of interoperability with the SMF ecosystem. 20 direct splices between TNANF A and SMF-28 gave total losses of 0.44 ± 0.05 dB, of which 0.40 ± 0.03 dB was apparent in pre-splice alignment, likely due to mode shape mismatch. Fig. 3(e) shows TNANF A to SMF splice broken to reveal the glass weld. For TNANF B the best-case loss from MFD mismatch is 0.60 dB (Gaussian approximation), measure in Fig.3(c,d). 24 cleave-align cycles and 9 direct splices gave 0.34 ± 0.02 dB coupling and 0.52 ± 0.12 dB splice loss in excess of theoretical minima. These values can clearly be improved by adding mode-field matching (TNANF B) and anti-reflection coatings.

Conclusion

We have introduced a novel antiresonant HCF (TNANF) that by virtue of a reduced confinement loss allows a remarkable loss improvement when its dimensions are small and matched to SMF. By adding a further nested tube and optimising the structure, we have achieved the lowest loss ever reported in an HCF with a 250 μm coated outer diameter: 0.25 dB/km in the C-band, a reduction from the 1.7 dB/km achieved with DNANF. By changing the core size one can trade-off some straight loss for total bend insensitivity. This is a significant step towards an integrated SMF-HCF ecosystem for optical communications.

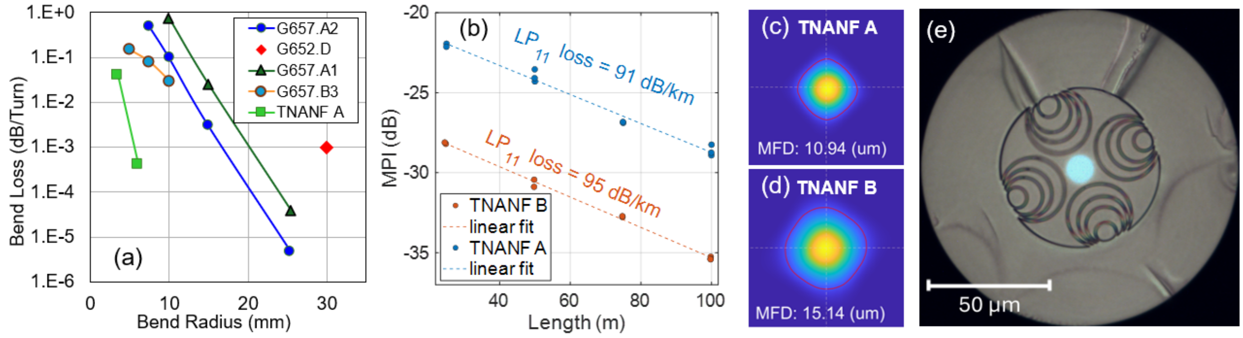

Fig. 3: (a) bend loss of TNANF A compared to SMF variants, (b) LP11 cutback loss measurement using S^2, (c,d) mode-field images and measured MFD, (e) splice imprint of the TNANF A microstructure on SMF-28.

Acknowledgements
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