# Hollow Core NANF with 0.28 dB/km Attenuation in the C and L Bands

**Gregory T Jasion[1,*], Thomas D Bradley[1,*], Kerrianne Harrington[1], Hesham Sakr[1], Yong Chen[1,2], Eric Numkam Fokoua[1], Ian A Davidson[1], Austin Taranta[1], John R Hayes[1], David J Richardson[1] and Francesco Poletti[1]**

*1 Optoelectronics Research Centre, University of Southampton, UK*
*2 Lumenisity Ltd, Unit 7, The Quadrangle, Romsey, S051 9DL, UK*
**Authors contributed equally to this work*

**Abstract:** We report an effectively single-moded, 1.7km long hollow core Nested Antiresonant Nodeless Fiber (NANF) with record-low 0.28dB/km loss from 1510 to 1600nm, which further reduces the loss gap with standard all-glass single mode fibers.

**OCIS codes:** Fiber design and fabrication (060.2280), Microstructured fibers (060.4005), Fiber optics and optical (060.0060) communications, Fiber properties (060.2400)

## 1. Introduction

Thanks to significant breakthroughs over the past few years, antiresonant hollow-core optical fibers (AR-HCFs) are generating hopes that they might one day become the ultimate optical fiber, simultaneously demonstrating the lowest attenuation, optical nonlinearity and chromatic dispersion over a broad bandwidth, whilst providing near-vacuum latency [1, 2]. Unlike previous generations of hollow-core fiber technology, AR-HCFs exploit coherent reflections from thin silica membranes and inhibited coupling from glass modes guided therein, to confine and guide light effectively in a central hollow-core [3]. Significant improvements in optical performance, modal quality and bandwidth were made possible over the last decade first by the introduction of a negative curvature core surround [4], then by fiber topologies with a single layer of non-touching tubes [5], and finally by the addition of small nested tubes; to increase the number of coherent air/glass reflections in the radial direction and thus reduce confinement loss - a design known as hollow core Nested Antiresonant Nodeless Fiber (NANF) [6, 7].

Since these first theoretical predictions, remarkable experimental progress has been reported with NANFs, thanks to refinements in the fabrication process and geometrical improvements in the transversal and longitudinal regularity of the fibers. In the space of only 5 years we have transitioned from the first feasibility demonstrations with losses of hundreds of dB/km [8, 9], to a fiber with conjoined tubes reaching 2dB/km [10], to the most recent and record low loss breaking NANFs: 0.5km long with 1.3dB/km [1] and 1.2km long with 0.65dB/km [2], the lowest reported loss in any HCF. Promisingly, all these fibers present nonlinearities 3-4 orders of magnitude lower than SMF and chromatic dispersion around 2-3ps/nm/km over several hundred nm [11], and models in good agreement with current experimental results predicts significant margins for further loss reduction.

Differently from other HCF topologies, nodeless HC-ARFs and in particular NANFs can be fabricated with an intrinsic high-order mode stripping mechanism that induces high loss for the high order core-guided modes, and thus enables effectively single mode operation after sufficiently long lengths [1,6]. This feature has been instrumental in the demonstration of the capability of NANFs to support data transmission, even through long distances, with 341km being reached so far in a recirculating loop including 4.8km of hollow core NANF [12].

Here, we report further progress to NANF technology producing a 1.7km NANF and more than halving the previous HCF loss record. The fiber presents small design improvements aimed at reducing microbend loss (smaller core diameter) and leakage loss (smaller azimuthal gaps, improved angular orientation of the tubes, better longitudinal uniformity). In addition, we have improved the loss measurement accuracy by increasing the cutback length to 500m to avoid measurement artefacts from spurious high order modes. As a result of these improvements, we have measured a loss of 0.28±0.04dB/km between 1510 and 1600nm, and only slightly higher (~0.3dB/km) up to 1640nm, values that are beginning to approach the requirements of long-haul transmission systems. The 625x loss reduction achieved in NANFs during the last 5 years including this result, are shown in Fig.1(a). Figure 1(b) and (c) show the SEM cross-section of this fiber and the OTDR plot (with the signal below the noise floor of the instrument due to very low backscattering coefficient), respectively.

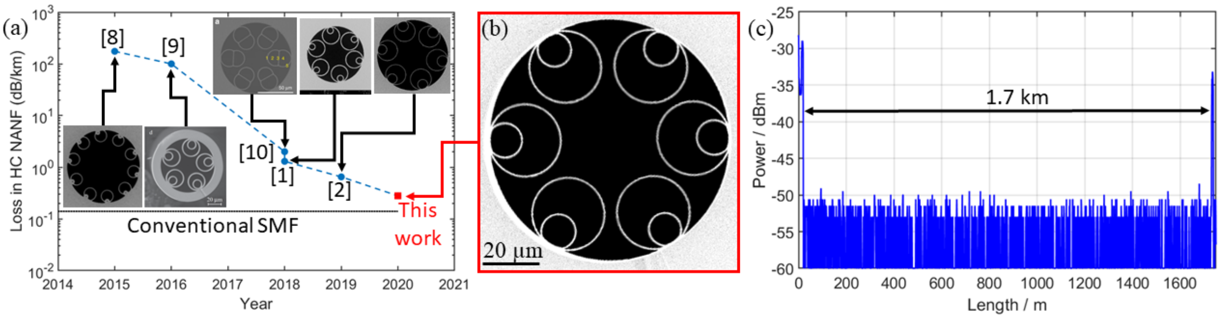


Fig.1: (a) Loss reduction in NANF (and conjoined tube) HCFs; (b) SEM of the present NANF; (c) OTDR trace of band A.

## 2. Fiber fabrication and characterization

The NANF reported here was fabricated with the same stack, fuse and two-step draw process as the fiber presented in [2], which we will refer to as NANF-SoA. Both consist of six pairs of nested silica capillaries arranged around a central hollow core. The geometrical differences are subtle but important. NANF-SoA had core diameter, average thickness and average azimuthal gap size of 37.2µm, 0.49µm and 5.12µm, respectively, which changed by 3-5% from one end to the other of the 1.23km long fiber. The NANF in this work has an average outer tube thickness of 0.50µm with inner tubes approximately 6% thicker, but a smaller core size (34.5µm) to reduce the impact of microbend loss, and a smaller average gap between the tubes (4.4µm) to compensate for the decrease in core size. Besides, it has a better longitudinal uniformity of <1% from end to end. A length of 2.8km was drawn from a single 20mm preform into two consecutive bands of 1.7km (band A) and 1.1km (band B) with no change in draw parameters. Images at all 4 ends look almost indistinguishable from the SEM image shown in Fig.1(b).

With the loss of the fundamental mode in recent NANFs dipping well below 1dB/km, we decided to investigate the loss of its higher order modes. Finite Element Method simulations from the SEM of the fiber indicated a loss of only 6-10dB/km for the 4 nearly degenerate $LP_{11}$-like modes, with higher order modes well phase matched to lossy tube modes and with considerably higher loss (>5000dB/km), Fig. 2(a). To corroborate this result experimentally, we characterized the modal content of the fiber in two different ways. Figure 2(b) shows a spatial and spectral ($S^2$) imaging cutback measurement from 500m to 10m. By integrating the power in the $LP_{11}$ mode peak/plateau in the two cases we estimated an $LP_{11}$ mode loss of ~11.4dB/km. In Fig.2(c) we measured the coherence function (i.e. Fourier transform of a broadband transmission measured on a high resolution OSA, with broadband excitation) of the same 500m piece. For delays below 2.6ps/m a distributed scattering plateau caused by $LP_{11}$ mode can be seen. By fitting its height and slope with a simple two-coupled mode propagation model we extracted an $LP_{11}$ mode loss of ~12 dB/km. Both experimental methods are thus in excellent agreement with the simulations.

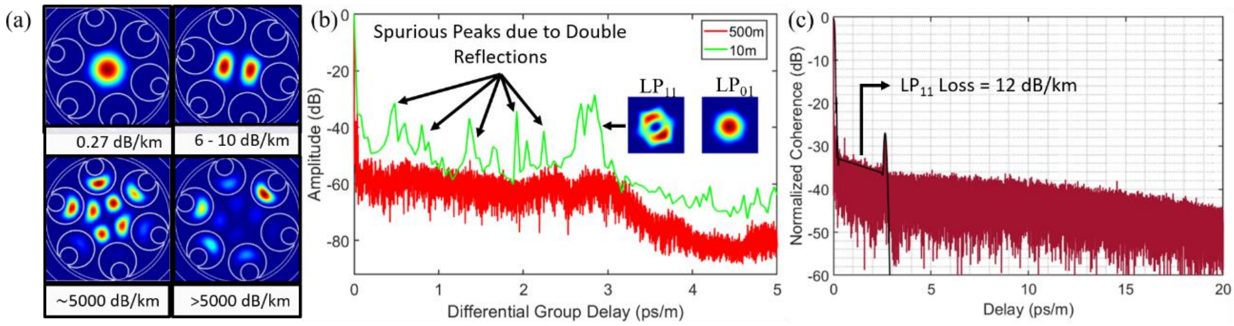


Fig.2: (a) Simulated modes of the fabricated NANF at 1550nm and their propagation loss; (b) Differential group delay through 500 m (red) and 10 m (green) of NANF; (c) Normalized coherence function measured through 500m of NANF.

The inferred $LP_{11}$ mode loss of 6-12dB/km also implies that over a few tens of meters the fiber will effectively behave as two-moded, and therefore cutbacks performed over such length are inevitably going to overestimate its real loss. To test this, we performed two consecutive cutbacks on band A: first from 1724 to 24m, representative of cut-back measurements performed up to now, and then from 1700 to a much longer 500m length, averaging the result of 3 cleaves at long and short lengths and using an incandescent white light source. In the first case, shown in Fig.3(a), we launched light through a mode-field-matched endlessly single mode fiber. The minimum measured loss was 0.60dB/km at 1535nm, the lowest loss reported to date for an HCF and an indication that the structural improvements worked. In the second cutback, shown in Fig.3(b), to minimize power fluctuations, we spliced the input SMF pigtail to the NANF under test through a suitable mode field adapter, and cutback to 500m. The comparison confirms our hypothesis: the significantly purer $LP_{01}$ launch obtained by using 500m of the same fiber to eliminate high order modes has the effect of greatly reducing the measured loss. As shown in the zoomed-in plot of Fig.3(c), the average measured loss of the fiber was 0.28 ± 0.04 dB/km from 1510 to 1600nm, and it remained ~0.3dB/km until 1640nm. In all plots, the uncertainty shown by the grayed region arises from cleave-to-cleave variability.

To further support this measurement, we also conducted a separate experiment using the virtually identical band B. Here we used a 1557nm DFB laser as a source, and passed it through ~5km of another NANF with matched core size to eliminate any spurious high order mode content. Band B was then spliced to this launch-conditioning fiber; the output power was measured, then the splice was broken and the input power was acquired. The 0.32dB of measured insertion loss for a 1.1km long fiber yield 0.29dB/km (also shown in Fig.1(c), with error bars), in excellent agreement with the previous cutback. As a final confirmation, we simulated confinement, microbend and surface scattering loss for the fiber, from an accurate representation of its cross-section extracted from the SEM image of Fig.1(b), as in [1]. The results are shown in Fig.3(d). As can be seen, the total simulated loss (red solid curve) matches well the spectral shape of the cutback measurement, if one ignores the 1350-1450nm water vapor and the >1650nm HCL absorption peaks which are not fundamental and could be reduced with drier fabrication processes and use of non-chlorinated glass. The figure shows that by far the biggest loss contribution comes from leakage or confinement, an angularly resolved map of confinement loss (at 1550nm) is shown in Fig.3(e). This indicates that light mostly escapes through the tubes, i.e. the small and regular inter-tube gaps play their leakage-prevention role very effectively.

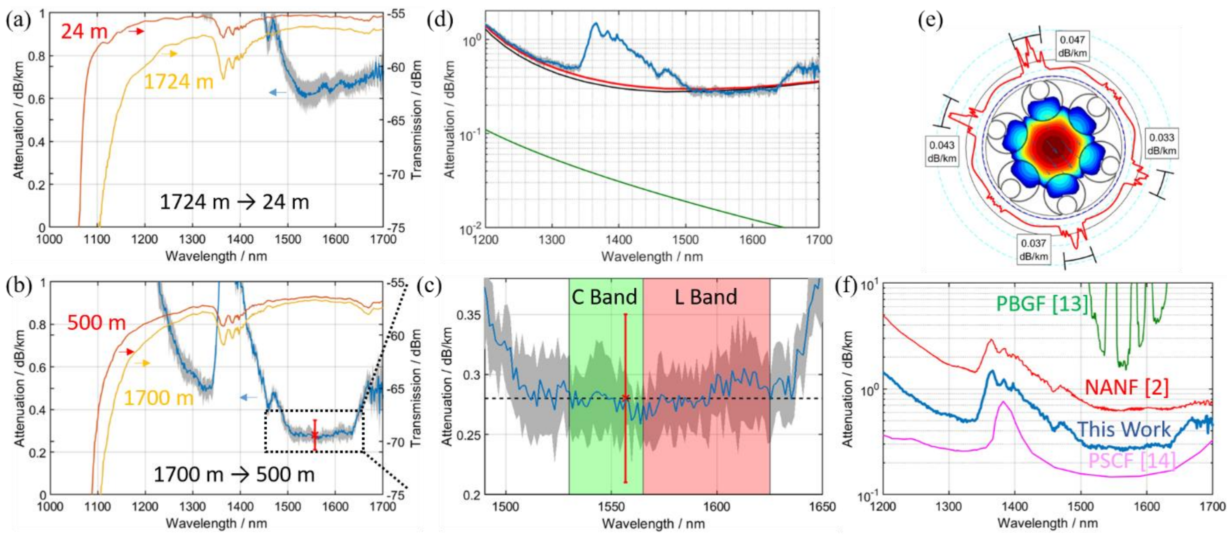


Fig.3: Transmission curves for (a) 1724-24m and (b) 1700-500m cutbacks, with corresponding attenuation (measurement uncertainty in gray); (c) zoomed in 1490-1650 nm low loss region; (d) simulated total (red), confinement (black) and microbend (green) loss compared with experimental (blue); (e) simulated mode field at 1550 nm and (f) spectral attenuation of SOTA HC-PBGF [13] (green), previous NANF [2] (red), NANF this work (blue) and pure silica core fiber [14] (pink).

The microbend-induced fraction is kept to very small values (~0.02dB/km at 1550nm) by a smaller core and use of improved coatings. Since these two loss contributions reproduce well the measured attenuation across the spectrum, we are inclined to conclude that surface scattering loss in these antiresonant fibers is lower than the empirically-fitted model in [6] would predict (~0.1dB/km). This is well possible, considering that the model was built upon very different hollow core photonic bandgap fibers and fitted without considering microbend and intermodal related losses, which we now know can play a non-negligible role. More work, beyond the scope of this paper, is required to strengthen this hypothesis, which, if confirmed, would lower the ultimate achievable expected loss in NANFs.

In Fig.3(f), we compare the attenuation of the NANF in this work to that of the lowest loss PBGF (1.7 dB/km over ~10nm bandwidth [13]) and of the previous record low loss NANF (0.65 dB/km over a 120nm bandwidth [2]).The figure illustrates the significant reduction in loss across the entire transmission window over a fiber reported just a few months ago, demonstrating once again the rapid development in NANF technology and its potential. For visual comparison, we also show the loss of a pure silica core fiber (PSCF) with <0.15 dB/km [14].

Modelling indicates that the measured loss ratio between fundamental and high order modes of 20x-30x, combined with the intermodal coupling inferred from the coherence measurement is adequate for short distance transmission over a few km. For much longer data transmissions over long-haul distances however, a higher $LP_{11}$ mode loss would be necessary to limit penalty-inducing cross-talk and intermodal interference. As it was shown in [6], this can be achieved by reducing the diameter of the inner nested capillaries to enhance phase matching between $LP_{11}$ and lossy capillary guided modes. Finally, we have found that despite a large mode field diameter (~23.8 µm), the small inter-tube gaps in this fiber make it coilable to splice-tray-compatible bend radii without excessive loss. At 1550 nm the measured bend loss is << 0.1 dB/m for bend diameters ≥ 8 cm and 0.2dB/m for a 4 cm diameter.

## 3. Conclusions

Through refinements in NANF fabrication and a more accurate loss measurement that reduces the high-order mode related bias, we report a hollow core fiber with improvements in both length and loss over the previous HCF record low loss result (1.2km, 0.65dB/km [2]). The NANF fabricated here has a length of 2.8 km (measured: 1.2km), and a loss of 0.30 ± 0.04 dB/km from 1500 to 1640nm, well in excess of C and L telecoms bands, with a spectrally flat region from 1510 to 1600nm at 0.28 ± 0.04 dB/km. More work is needed to further increase the loss of $LP_{11}$ modes for long distance data transmission without penalizing the $LP_{01}$, and to refine the surface scattering loss model, which currently seems to overestimate the loss. Simulations indicate that further loss improvements are possible.

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