0.174 dB/km Hollow Core Double Nested Antiresonant Nodeless Fiber (DNANF)

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Abstract: We report the first double-nested antiresonant hollow core fiber. The fiber matches the loss of commercial solid core fibers in the C-band (0.174 dB/km) and fundamentally improves it (0.22 dB/km) in the O-band.

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

1. Introduction

Guiding light or electromagnetic radiation in a hollow dielectric or metallic waveguide was proposed [1] and explored in depth [2] long before the advent of ultra-transparent glass. For over a century, the vision driving research on hollow core waveguides has been the search for vacuum-like speed, bandwidth, dispersion, linearity and possibly propagation loss. The key ingredient to unlock these benefits was a guiding mechanism able to contain light within a low refractive index core with minimum induced transmission penalties. Hollow core waveguide research peaked in the 1960s with metallic millimeter waveguides but was put on hold in the 1970s after the visionary work of Charles Kao [3] and pioneering research at Corning on glass purification methods [4] produced the first low loss solid core optical fibers that revolutionized the way we transmit data. The idea of guiding light in a flexible dielectric hollow core fiber (HCF), was only resumed in the 1990s by Philip Russell and his team [5]. They demonstrated that by creating a 2D photonic crystal in the cladding of a flexible fiber, it was possible to waveguide light in air, with only 1-2 dB/km propagation loss [6]. The following ten years of research, however, identified fundamental roadblocks preventing the realization of HCFs of such design capable of sub-1-dB/km loss and/or data transmission beyond a few tens of km. Meanwhile, an alternative guidance mechanism exploiting antiresonance from core-surrounding membranes and inhibited coupling to cladding modes was proposed and studied [7]. Early fibers suffered from ~1000 dB/km propagation losses (albeit over octave-spanning bandwidths), but progressive understanding and design refinements reduced these to ~30 dB/km in data-guiding structures made of simple non-touching glass tubes around the core [8, 9]. The next breakthroughs came with the realization that nested tubes were effective in reducing leakage [10] and that non-touching nested tube assemblies of appropriate number and size – the Nested Antiresonant Nodeless Fiber (NANF) design [11] – could theoretically achieve not only total losses well below 1 dB/km and potentially lower than silica, but also the effective single mode behavior needed for long distance data transmission [11].

NANF technology has progressed rapidly ever since, establishing itself as the most promising alternative to glass guiding solid core optical fibers. The world's-first sub-1-dB/km HCF was demonstrated in a 2019 NANF (0.65 dB/km [12]), and loss was further reduced to 0.28 dB/km across the C+L band in 2020 [13] and to 0.22 dB/km at the top edge of the L-band in 2021 [14] in a 6- and 5- nested tube NANF, respectively. The predicted efficient high-order mode stripping mechanism embedded in such fiber designs, resulting in a low level of intermodal interference (IMI), also allowed demonstration of coherent WDM data propagation through multi-thousand km distances in recirculating loop experiments [15]. Spurred by such encouraging research results, NANF technology has also reached early-stage commercialization, with cables already showing 0.5-0.9 dB/km loss and >1000 km recirculating loop transmission at 400 Gbit/s [16]. Such cabled fibers are already being deployed at various locations around the world.

Despite all this progress, antiresonant HCFs are still one small step away from the loss achieved by solid silica fibers. Several designs incorporating an increased level of cross-sectional complexity have been proposed with this aim. In this work, we focus our attention on the Double Nested Antiresonant Nodeless Fiber (DNANF) originally proposed in [11]. We show that adding one extra nested tube to each set of nested elements of a NANF is technologically feasible and optically effective in improving confinement and reducing leakage loss. We report the first HCF with a loss (0.174 dB/km) comparable to that of conventional telecoms fibers in the C-band, and appreciably better (0.22 dB/km) than what is fundamentally possible in a solid core fiber in the O-band.

2. Modelling, fabrication, and characterization

DNANF is made of sets of three similar-thickness nested tubes (one more than in NANF), each of which is solely attached to the outer edge of the microstructure, with an azimuthal gap between sets. In this work we chose 5 sets. Like in a Bragg fiber, adding tubes reduces light leakage – the dominant loss mechanism in these HCFs. Key to the design is also the presence of a cavity amongst the cladding tubes that is carefully sized (i.e. roughly comparable to the core radius, R_{core}) to out-couple higher order modes and thus substantially increase their loss. This is essential to minimize the intermodal interference (IMI) that can otherwise adversely affect the data transmission performance of HCFs [17]. For DNANF, such a cavity can be positioned between the large and middle tube (z_1), between the middle and small inner tube (z_2) or inside the small tube (z_3), as shown in Fig. 1a. Fig. 1b compares confinement loss simulations for the three different designs, all with a core diameter, D_{core}=28 µm. In each case, an optimum size of the cladding cavity exists at which the lowest loss high order mode (LP$_{11}$) is phase-matched to the fundamental cavity mode and hence strongly attenuated, however, this occurs for different corresponding levels of LP$_{01}$ loss. For a target LP$_{01}$ confinement loss of, for example, 0.1 dB/km, the z_2 design can induce 1000x higher loss for the LP$_{11}$ mode, as compared to just 50x and 100x for the z_1 and z_3 cases, respectively, and it was therefore chosen for this work. Fig. 1c shows the simulated bend loss of a z_2 design, where a fiber coiled at a diameter of 20 cm is predicted to incur only ~0.05 dB/km of additional bend loss. The mode field and loss of the target DNANF are compared to a NANF of otherwise identical structure in Fig. 1d; DNANF has ~10x lower leakage loss through the capillaries and gaps.

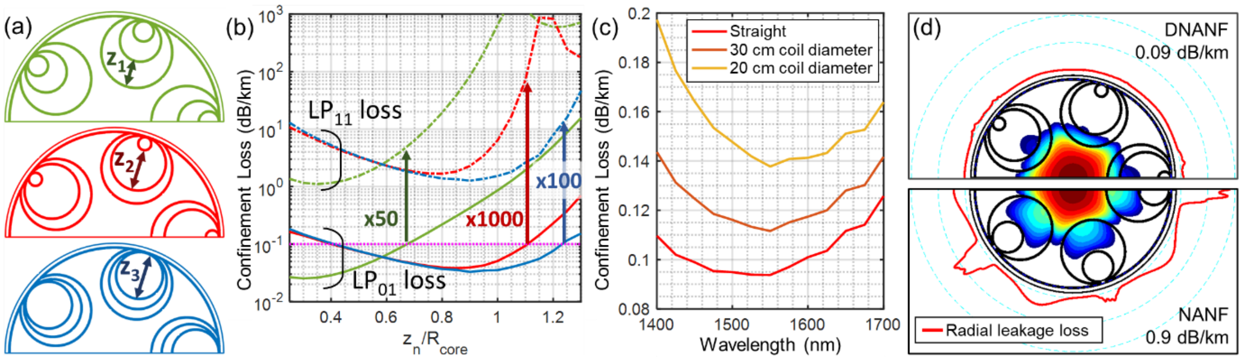

Fig. 1. (a) DNANF with z_1, z_2 and z_3 designs; (b) Confinement loss at 1550 nm of LP$_{01}$ and LP$_{11}$ modes for D_{core} = 28 µm; (c) loss in bend of a z_2 design fiber with z_2/R_{core}=1.1; (d) Mode field comparison between target DNANF and equivalent NANF.

Having selected the target structure, we fabricated the primary preform using the well-established stack, fuse and draw approach already used in NANFs [12-14]. The preparation of a DNANF primary preform only requires the addition of 1 nested tube per group and therefore represents only a modest increment in complexity over a conventional NANF. The added tubes in DNANF allow ultra-low leakage loss at a smaller core size, R_{core}, than typically used in NANFs. Since microbending loss is predicted to scale roughly as R_{core}^{10} in these fibers, smaller core sizes can considerably improve the fiber's microbend insensitivity and as a result reduce susceptibility to cabling induced loss. For this reason, in this first prototype we targeted a core diameter of 28 µm (the low loss results in [12] and [13] were achieved in NANFs with D_{core}=34.5 µm), for which simulations in Fig. 1 predict a fundamental mode leakage loss of ~0.1 dB/km. Fig. 2a shows the cross-section of the fabricated 3.37 km long fiber. The average diameters of the nested tubes are 29.0 (large), 23.4 (middle) and 8.1 µm (small), with an average membrane thickness of 478, 477 and 392 ±30 nm, respectively. All these parameters change by only 1-3 % from one fiber end to the other. The azimuthal gaps are 4.6±1 µm and only change by 0.6 µm along the length. To measure its loss, we performed a cutback from 3368 m to 273 m. We launched white light from a tungsten-halogen source using a spliced and mode-field adapted single mode patchcord and collected it into an OSA through a bare fiber adaptor. The results are shown in Fig. 2b and 2c, where the datasheet loss of Corning SMF-28e+ and that of two pure silica core fibers ([18] and [19], the current low-loss record holder), are shown for comparison. Our DNANF has two low-loss windows, in the O and S/C band, separated by gas absorptions from water vapor present within its core (1342-1512 nm). In the O band it presents the lowest loss ever measured in an optical fiber, 0.22 dB/km from 1300 to 1340 nm. In the S/C-band the loss is 0.174 ± 0.031 dB/km from 1500 to 1560 nm, where the ±1σ uncertainty includes cleave and OSA errors, length uncertainty, and light source drift. Fig. 2c also shows a separate independent 1550 nm insertion loss measurement using a laser diode (black square). The measured loss of 0.147 ± 0.024 dB/km overlaps with the uncertainty of the white light measurement, which gives us confidence about these results.

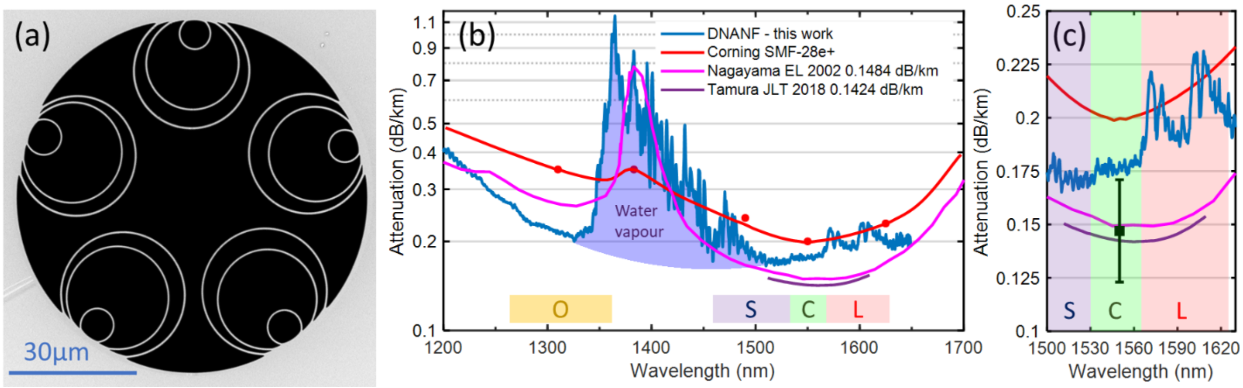

Fig. 2. (a) SEM of the 28 µm core DNANF; (b) measured DNANF cutback loss, compared to Corning SMF-28e+ and pure silica core fibers [18,19]; (c) zoom of loss in the C and L bands; the black square is a separate insertion loss measurement with a 1550 nm laser diode.

To investigate the fiber's higher order mode suppression, we measured its IMI. We characterized the intermodal interference using 3 km of DNANF, pigtailed at both ends with SMF-28, by sweeping a tunable laser source (<10 kHz linewidth, 200 µs detector integration time). Applying a sliding window to the measured spectrum, we calculated the IMI as in ref. [20]. We found a 2.5 THz (~20 nm) window, wide enough to distinguish coupling events in the fiber spaced >15 cm apart yet able to filter out spurious signals from the spliced ends, to be a good compromise. The IMI shows some spectral oscillations but remains between -54 and -58 dB/km (Fig. 3a). To put this into context, the IMI of the 5 tube NANF used in a recent 4000 km recirculating loop experiment was estimated to be between -45 and -55 dB/km [15], while a value of -60 dB/km is predicted to be low enough to cause no practical impact on long-haul transmission [17]. The fiber's PDL, measured through Jones Matrix eigenanalysis, was 0.06 dB at 1550 nm.

In an attempt to obtain an indirect confirmation of the quality of the fabricated fiber, we spliced the 3 km DNANF described here to another 2 km piece with similar characteristics and tested the 5 km fully connectorized assembly in a 10 Gbit/s commercial ADVA OOK low-latency testbed at 1550 nm (Fig. 3b) and with a Ciena Wavelogic Ai 400 Gb/s coherent system, in which one channel was tuned across the C-band (Fig. 3c). In both cases, the performance through the fiber was indistinguishable from the back-to-back case. Two channels (dashed lines in Fig. 3c) were put on soak test for over 10 hours with 400 GbE live traffic, returning zero (post-FEC) errors. Although future tests with longer fibers/recirculating loops will be essential to determine the real transmission potential of this technology, these simple tests provide a first indirect confirmation of the excellent single mode behavior of the fabricated fiber.

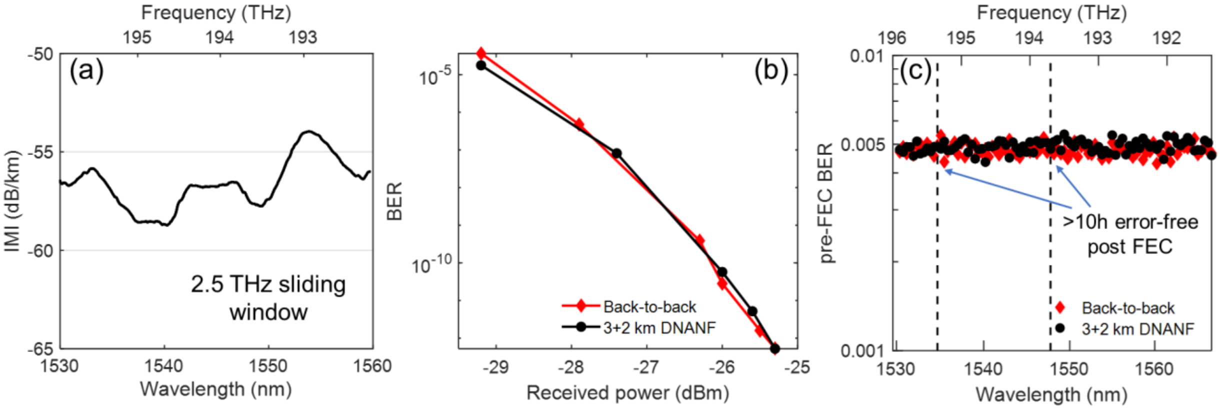

Fig. 3. (a) IMI measured with a 2.5 THz sliding window; (b) 10G BER curve at 1550 nm through 5 km of DNANF; (c) 400G pre-FEC BER for a single channel tuned across the C-band of the same 5 km fiber.

3. Discussion and conclusions

We have reported a new record-low HCF loss, based on a novel double nested (DNANF) structure. Its increased cross-sectional complexity requires only a modest modification to the well-established NANF fabrication procedure, with clear optical performance advantages. The DNANF reported here simultaneously achieves the lowest loss ever reached by an optical fiber in the O-band, (0.22 dB/km at 1300-1340 nm vs 0.35 dB/km for Ge-doped SMF and 0.27 dB/km for pure silica core fibers) and 0.174±0.031 dB/km across the C-band, lower than commercial terrestrial G.652 fibers and not far from pure silica core loss records. These results are achieved despite a smaller core size (28 µm) than previously used for C-band operating HCFs, which is predicted to reduce SMF interconnection and cabling-induced losses (to be proven in due course). Thanks to careful design optimization, the measured IMI of better than -54 dB/km is similar or better than previously reported HCF [15], and produces no measurable BER penalty at 10G and 400G through 5 km of fiber. More stringent tests over longer fiber lengths are needed to assess its full potential.

After 30 years of research, HCFs have finally reached the loss level of solid core fibers. Analysis of the loss mechanisms of the prototype fiber reported here leads us to believe that DNANF technology still has margin for improvement. Further optimizations in fiber design and cabling procedures might one day yield *cabled* HCFs with a lower loss than possibly achievable in a conventional solid core optical fiber, whilst also benefiting from the other well-known advantages of latency, nonlinearity and dispersion in hollow core optical fibers.

This project acknowledges funding from the ERC (LightPipe, g.a. 682724), the UK RAEng and EPSRC (Airguide Photonics, EP/P030181/1). CIENA and ADVA and are gratefully thanked for advice and the loan of equipment, and Lumenisity technical staff for various contributions.

References

[1] L. Rayleigh, Philos. Mag. J. Sci. 47, 375 (1899).
[2] R. J. Boyd et al., Bell Syst. tech. j. 56(10), (1977).
[3] K. Kao et al., Proc. Inst. Electr. Eng. 113, 1151 (1966).
[4] D.B. Keck et al., Appl. Phys. Lett. 22, 307 (1973).
[5] R. F. Cregan et al., Science 295, 1537-1539 (1999).
[6] P. J. Roberts et al., Opt. Express 13, 236 (2005).
[7] F. Benabid et al., Science 298, 399 (2002).
[8] B. Debord et al., Optica 4, 209 (2017).
[9] J. Hayes et al, J. Light. Technol. 35, 437 (2017).
[10] W. Belardi et al., Opt. Lett. 39, 1853 (2014).
[11] F. Poletti, Opt. Express 22, 23807 (2014).
[12] T.D. Bradley et al., ECOC 2019 PDP, paper PD.3.1.
[13] G. T. Jasion et al, OFC 2020 PDP, paper Th4B.4.
[14] H. Sakr et al, Proc. OFC 2021 PDP, paper F3A.4.
[15] A. Nespola et al, OFC 2021 PDP, paper F3B.5.
[16] A. Saljoghei et al, arXiv 2021 [e-print: 2106.05343] .
[17] P. Poggiolini et al., J. Light. Technol. (2022) Early Access
[18] K. Nagayama et al., Electron Lett. 38 (20), 1168 (2002).
[19] Y. Tamura et al., J. Light. Technol. 36(1), 44 (2018).
[20] S. Ramachandran et al., Phot. Tech. Lett. 15, 1171 (2003).