Hollow Core DNANF Optical Fiber with <0.11 dB/km Loss

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Abstract: We report the fabrication of a hollow-core DNANF with a geometry extensively optimized for minimum loss. Three independent loss measurements average 0.08±0.03 dB/km at 1550 nm, the lowest attenuation ever achieved in an optical fiber. © 2024 The Author(s)

1. Introduction

Since 1970 many glass types have been developed and investigated to select the one with the lowest propagation loss for optical communications. Multicomponent glasses such as soda lime [1], fluorides [2] and chalcogenides [3] had theoretical potential for ultra-low loss, but this could never be achieved in real fibers. On the other hand, thanks to the introduction of vapor phase deposition techniques to reduce metal ion contaminants to ppb levels and of dehydration processes to virtually eliminate the hydroxyl content, fused silica has attained levels of near-infrared optical transparency that have been, to date, unrivalled. Due to its availability, low price, mechanical robustness and low attenuation, synthetic fused silica has become the go-to solution for optical fiber communications, supporting intercontinental communications and a global production of >500 million fiber km per year. After five decades of progress, the fiber optics community is still capable of achieving small improvements in the optical transparency of silica fibers [4]. However, the loss is so close to the fundamental limit that, despite significant efforts, in the last 22 years it could only be decreased by 0.0087 dB/km (from 0.1484 in 2002 [5] to 0.1397 dB/km in 2024 [4]).

For the last two decades, hollow core fibers (HCFs), guiding light in an air rather than a glass core, have been recognized as a potential way to overcome Rayleigh scattering and infrared absorption, and thus to achieve lower losses than silica [6]. In 2014, a new HCF design was proposed, the Nested Antiresonant Nodeless Fiber (NANF) [7]. When all its loss contributions were accounted for, modelling predicted that it might be able to break the silica loss limit. Over the last decade, fibers fabricated according to this design have indeed achieved losses lower than fundamentally achievable in silica at most wavelengths of commercial and scientific interest, including 700 nm [8], 850 and 1060 nm [9], 1310 nm [10] and 2000 nm [11]. The S, C and L bands around 1550 nm have remained the last spectral regions where glass can still achieve a lower attenuation than air-guiding fibers. Two years ago, a double nested HCF (DNANF) was reported with a loss of 0.174 dB/km at 1550 nm [10], comparable to that of germanium-doped all-glass fibers, but still higher than the lowest loss demonstrated in pure silica core single mode fibers.

In the last two years we have worked to understand how to further reduce the loss in DNANF. We have improved fabrication methods and recipes, increased fabrication uniformity, improved and validated loss models through targeted experimental campaigns, and used these models to extrapolate the ultimate limits of the technology. In this work, we report the fabrication of a fiber close to the predicted optimum point and with a loss that three independent measurement methods assess to be below 0.11 dB/km, with a statistically derived mean of 0.08±0.03 dB/km.

2. Loss model fitting, loss optimization, fiber fabrication and characterization

The work started with a rigorous validation of our loss models. We acquired SEM images of both end faces of 15 fabricated DNANFs with five sets of nested tubes, like the one in ref. [10], but with a variety of geometrical parameters (tube sizes and membrane thicknesses). We then extracted their cross-sectional geometries and simulated their respective losses with known models for the confinement, surface scattering and microbending components [12]. Next, we used the measured loss curves to identify a unique fit for the non-directly measurable coefficients used within the surface scattering and microbending loss models [12]. In doing so we ensured that the best agreement between measured and total simulated loss, was achieved simultaneously for all fibers. Two examples of the excellent agreement obtained are shown in Fig.1a (Fiber A and B – both with a core diameter of ~26.5 µm but different tube sizes). We then used this calibrated loss model to optimize the fiber geometry and establish the lowest total loss compatible with an intermodal interference (IMI) value of <-55 dB/km. Fig.1b shows one slice of the multidimensional space optimization. In order to minimize microbending loss in cables, we settled on a core diameter, D_{core}, of 29 µm, slightly smaller than optimum but capable of achieving 0.08 dB/km, in theory (Fig.1b). We then fabricated a fiber with geometrical parameters as close as possible to optimal (Fiber C).

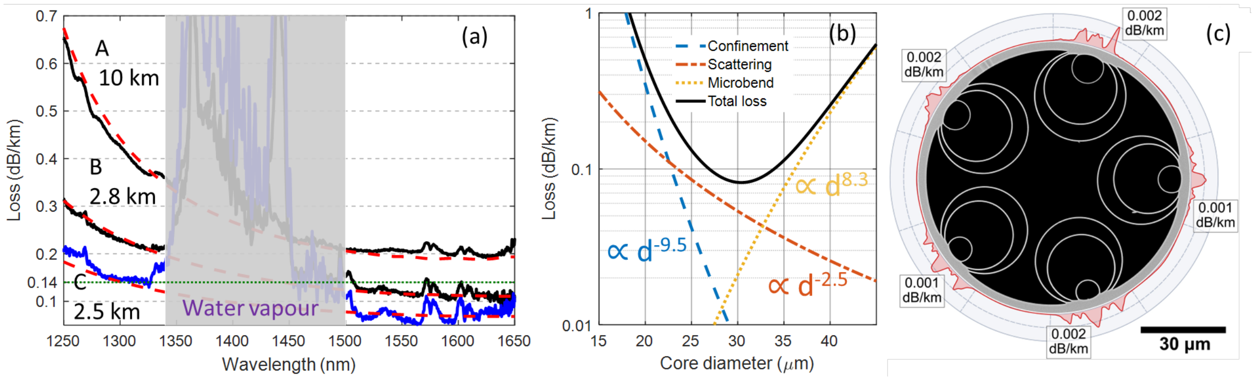

Fig. 1. (a) Measured (solid) and simulated (dashed) loss of fibers used for design optimization (A,B) and optimum design fiber (C); (b) Core size optimization; (c) SEM image of fabricated DNANF C, overlaid with the simulated azimuthal leakage components.

The SEM cross section of Fiber C is shown in Fig. 1c, together with the simulated radial Poynting vector, showing that the leakage contribution from all azimuthal directions is extremely low. The fabricated fiber has a core diameter of 28.8±0.5 µm. Note that the previous HCF record in [10] was achieved in a DNANF with D_{core}=28 µm but with un-optimized tube sizes. Our study indicated that subtle variations in these parameters can produce substantial differences. The average diameters of the nested tubes are 31±1.5 (large), 28.8±2 (middle) and 10.0±3µm (small), with thicknesses producing fundamental antiresonance centered at 1550 nm. The average azimuthal gaps are 4.4±0.5 µm.

Fig. 2 illustrates the results of *three independent loss measurements* carried out on DNANF C. *First*, we did two cutback loss measurements: one (long) from 4.12 km to 1.6 km and a second (short) from 2.52 km to 20 m. For both we used a stabilized tungsten halogen light source coupled to the fiber under test via a mode-matched launch, took measurements for three repeated cleaves and averaged the associated measured powers. As can be seen in Fig.2a, there are subtle differences, but despite the different cutback length the results are very similar. They are compared with the state-of-the-art loss of pure silica core SMF [5, 13] and with a in-house loss measurement of a commercial G657 fiber. The highest measured loss for DNANF C from the two cutbacks at 1310, 1550 and 1625 nm is 0.14±0.03 dB/km, 0.06±0.03 dB/km and 0.08±0.04 dB/km, respectively. No attempt was made to purge the fiber preform, and as a result non-intrinsic absorption loss from atmospheric gases are observed in the 1330-1500 nm (water vapor) and in the 1570-1585 and 1600-1615 nm (carbon dioxide) regions. The simulated loss obtained from the fiber SEM image without using any free-parameters broadly agrees with the cutback (total loss at 1550 nm: 0.081 dB/km), and shows that the surface scattering, confinement, and microbending contributions are 68, 11 and 21 %, respectively.

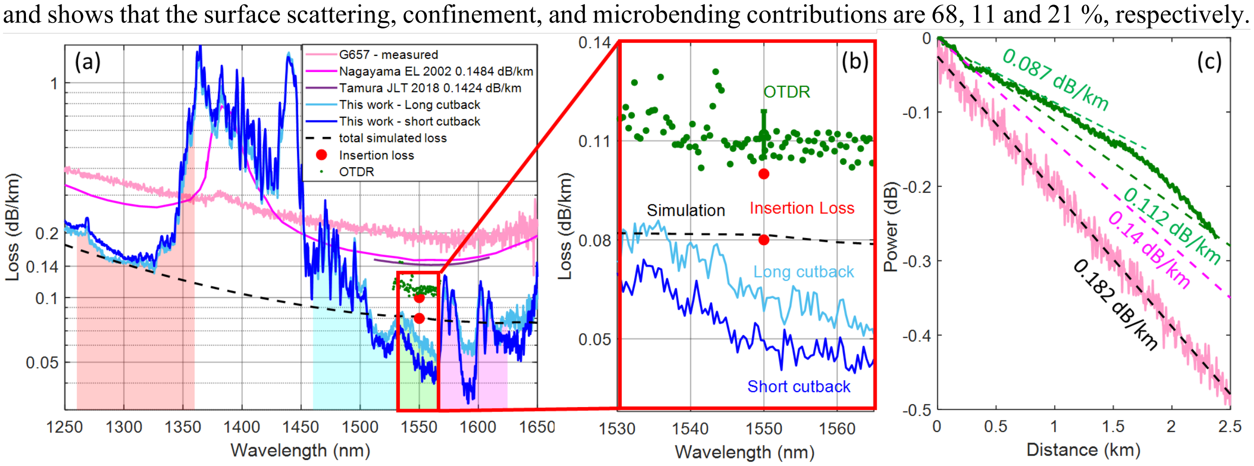

Fig. 2. Loss measurement of DNANF C (cutback, OTDR and insertion loss) compared to its simulated loss and to state-of-the-art SMFs; (b) zoomed in measurement showing the C-band only; (c) Bi-directional OTDR on DNANF-C, compared with G652 SMF.

Next, we obtained a *second* independent loss determination via a bi-directional Optical Time Domain Reflectometry (OTDR) method. The OTDR (Viavi E41DWDMC) was amplified to compensate for the DNANF's reduced backscattering [14] and suitably coupled into the DNANF under test. Use of the bi-directional method [15] eliminates the impact of any gas pressure gradients along the fiber length on the backscattering coefficient and allows to extract the change in backscattering exclusively caused by the fiber loss. Fig. 2c shows the loss measured with this method in DNANF C at 1550 nm with 30 ns pulses, compared to that measured, with the same method and instrument, for a G652 fiber (nominal loss of 0.18 dB/km). As can be seen by the total power drop over the fiber length, the overall loss of the HCF is 0.11 dB/km (with a estimated uncertainty of +/-0.01 dB/km). The measurement also shows that a 1.5 km subsection of the fiber has a loss as low as 0.087 dB/km. The same OTDR measurement was then repeated across the C-band (green dots in Fig. 2b). Lastly, we also performed two insertion loss measurements with a 10 nm wide unpolarized source centered at 1550 nm and a power meter, using bi-directional OTDR to measure the coupling loss between launch and fiber under test. This returned a *third* independent determination for the loss, with values of 0.08 and 0.10 dB/km (red dots in Fig.2b) obtained from two separate measurements. Use of independent measurement methods serves to reduce the impact of the systematic bias of each method. From the set of three independent measurements (Cutback, OTDR, and Insertion loss), we conclude that: i) the loss of the fiber under test is lower than 0.11dB/km; ii) the combined averaged loss value is 0.08±0.03dB/km.

To analyze the modal purity of the fiber, we measured the intermodal interference (IMI) over its 2.5 km length using a tunable laser source with <10 kHz linewidth and a power meter (200 μs integration time) and applied the swept wavelength method as in ref. [16]. The fiber shows IMI of -63 dB at 1555±1 nm and <-57 dB across the wavelength range 1555-1565 nm. In the same range, Jones Matrix eigenanalysis returned a mean PDL of 0.04 dB over 2.5 km.

Fig. 3 shows the loss of DNANF C, compared with that of other NANFs and DNANFs reported in the past 3 years. Hollow core fiber technology has now reached a level of optical performances such that almost everywhere in the near infrared spectrum (apart from the water-vapor region around 1400 nm) it can offer a lower attenuation than fundamentally possible with the best solid core glass fiber. The figure also shows a prediction of the achievable loss for an optimum DNANF produced with current fabrication processes, based on the calibrated loss model described above (red dashed line). This indicates that additional margin exists for further performance improvement in every region, and, most importantly, that HCFs open the possibility to obtain ultralow propagation losses for optical communications and other applications even at wavelengths significantly different from the conventional C-band.

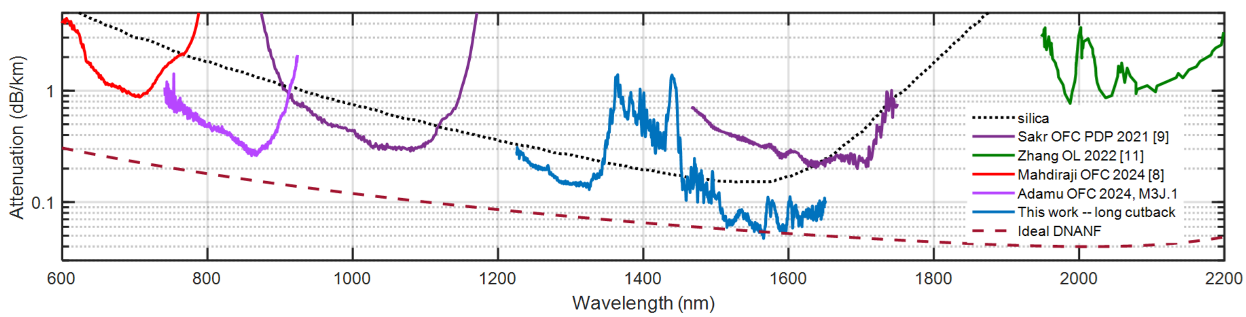

Fig. 3. Measured fiber loss of DNANF C (blue trace), compared to state-of-the-art NANF and DNANF fibers. The black dotted trace shows the intrinsic loss limit for pure silica core SMF and the red dotted trace shows the precited achievable loss for current DNANFs.

4. Conclusions

After a systematic calibration campaign for our DNANF loss models and through rigorous structural optimization, we have produced a fiber with geometrical properties (core and tube sizes, membrane thicknesses and inter-tube gaps) suitable for ultralow loss. Over a relatively short length of 2.5 km, its measured loss agrees well with simulations. Three independent and meticulously executed measurements indicate that the fiber loss at 1550 nm is 0.08 ± 0.03 dB/km, the lowest loss ever achieved in an optical fiber. The cutback also indicates an absolute low loss record of 0.15 ± 0.03 dB/km at 1310 nm, and an IMI better than -57 dB/km, adequate for long-haul data transmission [17]. The fiber has a margin for structural and performance improvements. More work is needed to produce the longer lengths required to improve the loss measurement accuracy, and to remove absorbing gas species from the hollow core to support ultra-wide transmission bands. While the impact of this technology will depend on our ability to scale up its production volumes and to maintain such optical performances after cabling, the demonstration that a hollow core fiber can achieve lower loss than silica anywhere in the spectrum is a landmark result for fiber optics.

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