10.9km Hollow Core Double Nested Antiresonant Nodeless Fiber (DNANF) with 0.33dB/km loss at 850nm

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Abstract: We report a double-nested antiresonant hollow core fiber designed for ~850nm operation. The measured fiber loss is 0.33dB/km at 850nm across a single span of 10.9km.

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1. Introduction

Hollow core fibers (HCFs) have been heavily researched in the last decade because of their promise to produce lower loss than standard single mode glass fibers (SMFs) over a wider bandwidth, whilst inherently providing the advantage of ultralow nonlinearity and latency [1, 2]. Recent understanding of the scaling rules for the various loss contributions of HCFs indicates that, by modifying geometrical parameters in the fiber's cross section, the minimum propagation loss of HCFs can in principle be shifted to arbitrary wavelengths in the near infrared [2]. This is in clear contrast to SMF, where the minimum loss value is intrinsically frozen to the C-band, i.e., in the wavelength region where the Rayleigh scattering loss and the infrared absorption curves intersect. The possibility of achieving loss below that of SMF at wavelengths shorter than 1550 nm has already been demonstrated in a few publications. For example, five tube Nested Antiresonant Nodeless Fibers (NANFs) with a loss of 0.6 dB/km at 850nm and 0.3 dB/km at 1060nm was reported [3]. In this work we focus on improving the attenuation of a HCF designed for operation at 850 nm, a wavelength often used in short distance optical communication links, using inexpensive high-speed GaAs VCSEL and silicon detector-based optics within datacenters. Here we focus on the latest antiresonant HCF design, where an additional nested tube is added to produce a Double Nested Antiresonant Nodeless Fiber (DNANF). Through improved fabrication procedures, we present the longest single span length of low loss, antiresonant HCF ever reported, about 10.9 km. The fiber has a measured loss of 0.33 dB/km at 850 nm, the lowest attenuation ever measured at this wavelength. This is a factor of ~4.5 times lower than the ~1.5 dB/km loss that fused silica can fundamentally achieve at these wavelengths due to Rayleigh scattering [4], and ~7.5 times lower than what 50 µm core graded-index fibers typically offer (e.g. 2.3 dB/km for OM4 fibers) [5]. Combined with extremely low chromatic dispersion of 2-3 ps/nm/km, this offers promising opportunities to extend the reach of optical communication links in the 850 nm waveband.

2. Fabrication, Characterization and Modelling

The DNANF microstructure is composed of five equally spaced resonator sets. Each set comprises three nested glass tubes, where each tube is fused to the next bigger tube and to the inner edge of the solid glass cladding surrounding the microstructure (see insets in Fig. 1), at positions with an average angular separation of 72 degrees. The three tubes in each set are designed to have carefully engineered, decreasing diameters and approximately matching thicknesses, to satisfy the anti-resonance conditions at the operating wavelength of ~850nm. The five outer tubes determine the size of the hollow core (R,) and that of the inter-resonator azimuthal gaps. Similar to previously reported structures [1], the role of the double nested structure is twofold: firstly, the additional nested tubes act to decrease the leakage loss as compared to simpler NANF structures; further, they form a cavity (located between the middle and the inner elements), which is designed to suppress the propagation of higher-order modes in the hollow core through resonant outcoupling. The additional tubes in DNANF allow ultra-low leakage loss at a smaller core size than is typically feasible in NANFs.

The DNANF reported in this work was fabricated from a preform via a now well-established stack, fuse and draw method [1,2]. Use of pressure differentials, selectively applied to the various volumes within the preform, allowed precisely matching the final fiber structure to the chosen design, and ultimately achieving low loss guidance at the target wavelength. The fiber (Fig.1) has a core diameter of 28 µm and average resonator sizes of 25.8µm, 19.6µm, 5.1µm, respectively. The average size of the azimuthal gaps, and the relative size of the main resonator cavity, z_2/R, were measured to be 5.3±0.5µm and 1.03±0.02, respectively. The membrane thickness was designed to center the fiber's second transmission window at the wavelength of approximately 850 nm, and the core was chosen with a small enough diameter to reduce the impact of the microbend-induced effects that cause additional loss and undesired coupling to higher order modes. The availability of accurate electromagnetic [2] and fluid dynamics modelling tools [6] enables us to achieve stable draws. This was exploited to increase the size of the preform and improve the yield of the fiber drawing process.

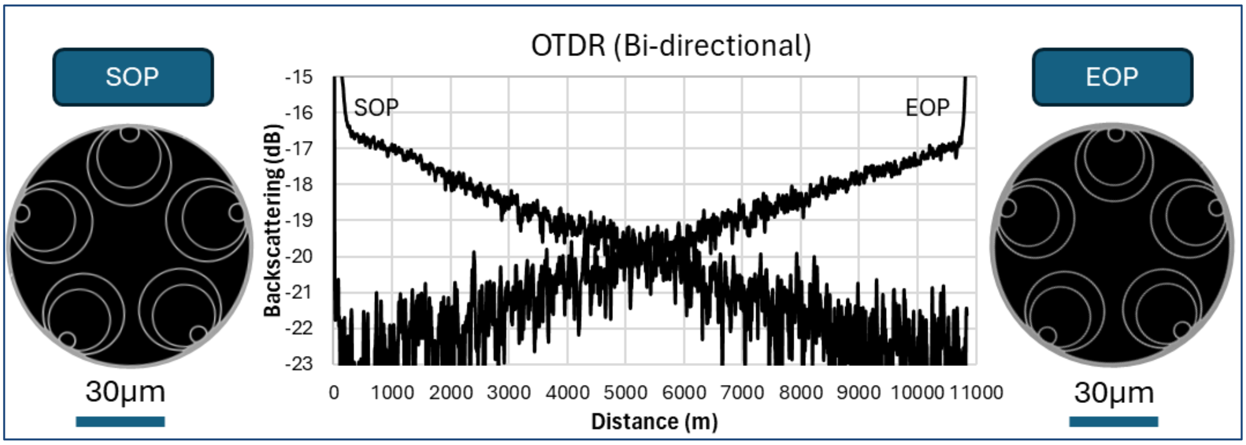

Fig.1: Bidirectional OTDR measurements showing excellent loss uniformity across the 10.9km fiber length. The two insets show SEM images of the DNANF at each end (SOP & EOP indicate the Start of Pull and End of Pull ends of the DNANF span).

Fig.1 shows the results of bi-directional optical time-domain reflectometry (OTDR) measurement of the 10.9km DNANF span, demonstrating transmission throughout the full fiber length and a uniform loss vs length profile. Note that for this measurement we chose a wavelength of 1625nm, falling within the first transmission window of the DNANF (see fibre transmission in Fig.2). The two insets show Scanning Electron Microscope (SEM) images of the microstructure at the two ends of the span, suggesting excellent structural consistency. As best we are aware, this is the longest ever reported span of low loss HCF, nearly twice longer than previous report of NANF [7], three times longer than DNANF[1] and approaching the longest span of PBGF HCF (11km) reported back in 2016 [8], which however was designed for operation at 1550nm and had significantly higher transmission loss (5.2dB/km).

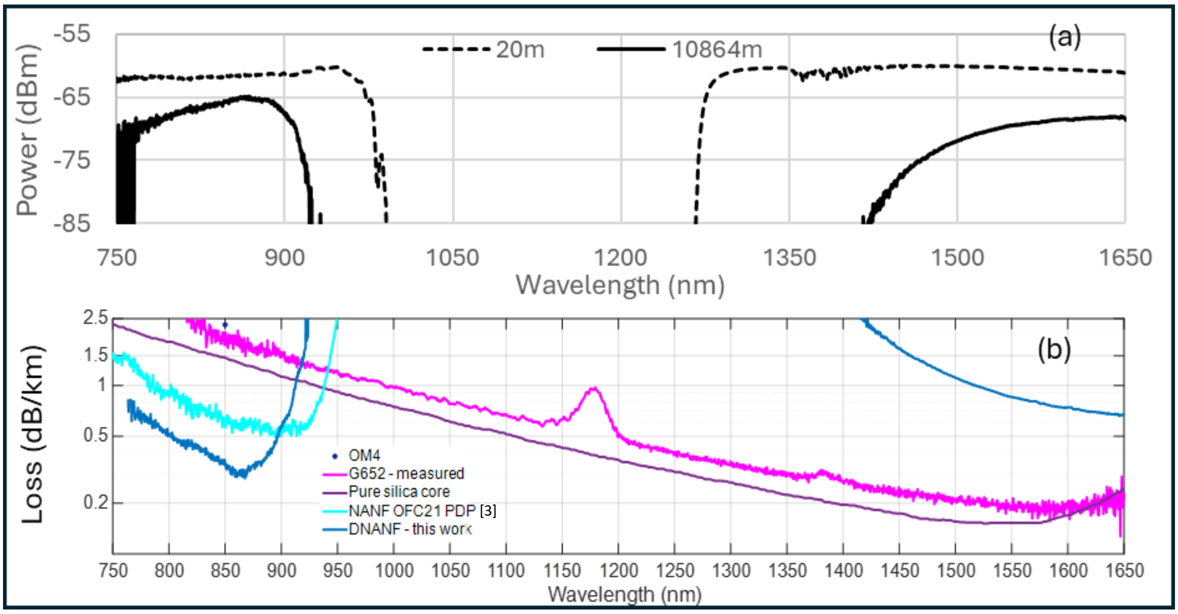

Fig.2. (a) Spectral transmission of the DNANF HCF, clearly showing the first and second antiresonant transmission wavebands at 1500 and 850nm, respectively. The fiber is optimized for operation in the 2nd waveband. (b) Measured cutback loss of the DNANF in this work, compared to previous state-of-the-art NANF [3], pure silica core fibers [4, 9], G652 single mode fiber (measured) and OM4 multimode graded-index fiber [5].

The transmission loss of the DNANF was evaluated via a standard cutback method (10864m to 20m) using a stabilized tungsten halogen white light source and an optical spectrum analyzer (OSA); a mode-field-adapted single-mode patch cord was employed to selectively launch the light into the fundamental mode. The measured spectral transmission and loss are shown in Fig. 2(a,b). Two cutback measurements were performed on the fibre; here we quote the average loss value and ±1σ uncertainty which accounts for cleave and OSA errors, length uncertainty, and light source drift. The DNANF has a minimum loss of 0.30±0.02 dB/km at 860nm, which to our knowledge is the lowest ever reported in an optical fiber in this wavelength range, and approximately 50% less than the previous lowest loss value achieved in a NANF fiber (0.6 ± 0.15dB/km at 850nm in a 5-tube NANF, also operating in the 2nd window [3]). The loss at 850nm is 0.33dB/km, which is ~7x lower than that of commercial multimode graded-index fibers widely used in data center datacoms applications (e.g., OM4 fibers with a typical loss value of 2.3dB/km at 850 nm [5]). Furthermore, the low loss region (3-dB transmission) extends over a ~100nm wide wavelength region spanning from 800-900nm. The fiber also allows for relatively relaxed alignment tolerances, given its large (~20µm) mode field diameter, combined with a chromatic dispersion value (obtained through simulations) of just 2–3 ps/nm/km, significantly below the ~100 ps/nm/km of the solid core graded-index counterparts.

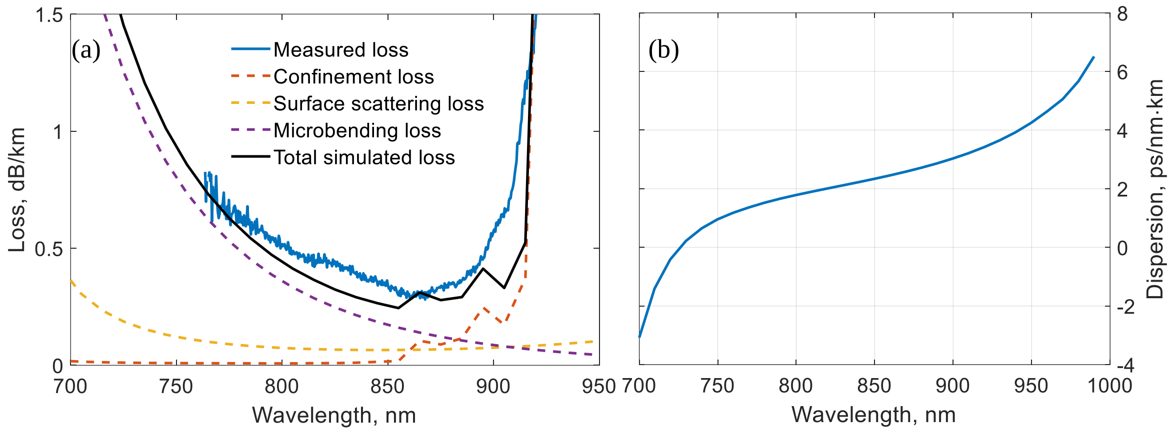

Fig.3. (a) Finite element simulation of transmission loss of the DANF, with individual loss contributions, compared with the measured spectral loss. In this waveband, the loss is dominated by contributions from microbending and surface scattering. (b) Simulated chromatic dispersion of the fabricated DNANF, showing a zero-dispersion wavelength at 725nm and only 2-3 ps/nm.km around 850 nm.

We show in Fig. 3 the results of finite element simulations performed on cross-section images of the fiber. These give insight into the various physical mechanisms contributing to loss and their relative magnitude. As can be seen (Fig 3a), in this waveband, the fiber attenuation is dominated by microbending and scattering from surface roughness, with leakage loss amounting to only 10^{-2}dB/km. The excellent agreement between modelled and measured loss further attests to the uniformity of the fiber along its length. Although not shown here, these simulations also reveal that the leakage-dominated minimum loss in the first antiresonant window is approximately 0.35 dB/km near 1800nm. The calculated dispersion curve in the 850nm band is shown in Fig.3(b), showcasing the low dispersion properties typical of the HCF DNANF design.

3. Discussion and conclusions

We have reported a new record-low loss hollow core fiber at 850 nm, achieved using a double nested (DNANF) structure. The fiber was produced in a single length in excess of 10 km and with excellent longitudinal stability and structural consistency. This is over three times longer than the DNANF reported at OFC 2022 [1], demonstrating promising improvements in production yield for these fibers. The measured loss of 0.33 dB/km at 850 nm, is the lowest loss ever achieved in an optical fiber at this wavelength. The loss remains <0.5 dB/km over a ~100nm wide wavelength interval centered at 850nm, in good agreement with modelling results. We believe these results open interesting opportunities for the use of HCFs in intra- and inter-datacenter applications, where they can bring not only a ~30% lower latency but also the potential to exploit cheaper transmission technologies.

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