Anti-Resonant, Mid-Infrared Silica Hollow-Core Fiber

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Abstract: In this paper we report the fabrication and characterization of a silica anti-resonant hollow-core fiber which shows guidance to 5.9μm and record low loss between 4.3 and 5.2μm despite a low glass jacket thickness.

1. Introduction

The mid-infrared (MIR) is important for a range of applications, from gas-sensing to power delivery [1,2], and the development of fibers capable of efficiently guiding these wavelengths over intermediate (1-100m) distances is thus of considerable interest. From a material absorption perspective silica may not seem the obvious choice, but with the advent of hollow-core fibers (HCFs), the guidance of MIR wavelengths has not only been shown to be possible but, due to silica fiber's technological maturity, that it may be the best option [3-9]. Silica HCFs also offer the advantage of low optical non-linearity, low latency, the ability to guide high average and peak powers without risk of damage and allow hundreds to thousands of meters of fiber to be fabricated from a single draw [4].

One outstanding issue is that low loss guidance requires a core on the order of 20-25 times the wavelength of operation (>100μm diameter in the MIR). This results in the need to make fabrication trade-offs – such as a large outer diameter (potentially >400μm) making fabrication and deployment challenging [5] or, in the case of an anti-resonant fiber (ARF), increasing the number of cladding tubes, thereby reducing the fibers ability to rapidly attenuate ("strip out") higher order modes (HOMs) [6,9]. In this paper we report a different approach, reducing the jacket glass thickness of a single-ring anti-resonant fiber (ARF) to only ~30μm. Our initial aim was to investigate the viability and effect of this approach, but in the process a fiber with remarkably low loss and bend insensitivity, considering its structure, has been realized. The details of this fiber are reported here.

2. Fabrication and Characterization details

The reported fiber was fabricated via a two-stage stack-and-draw process [4]. During the fiber draw inline fluid dynamic modeling [10] and a multi-zone pressurization system were used to achieve the desired structure (Outer diameter, OD = 358μm, Core = 132μm, Jacket thickness = 33μm, AR tube thickness ≈ 2μm). The fibers drawdown ratio was such that a total fiber yield of 400m was possible from the preform used, and hence ~70m of the target fiber was collected during the draw. However, future preforms and draws are anticipated to yield longer uaable lengths.

The fiber loss and bend-sensitivity were measured using an Arcoptix Arclight IR lamp (20W SiC globar, 1-25μm spectral range, NA=0.3 launch) and Rocket FTIR (2-6μm range, 2-stage TE cooled MCT detector). This set-up lacks the spectral density and sensitivity to characterize the full 70m band, hence a 4.1m length was selected. The fiber was arranged in a ~0.8m diameter loop, which was cutback to 1m. The bend-sensitivity of the same 4.1m length was measured prior to the cutback measurement by coiling it in a series of grooves cut in an acrylic sheet, with at least one full loop being measured at each diameter and the remaining fiber left straight or with a much larger diameter.

3. Results and Discussion

Fig.1(a) shows the result of the cutback measurement. The 1st anti-resonant (AR) window (guiding ~4-6μm) shows losses below 1dB/m from 4.5-4.7μm, with a minimum of 0.7dB/m at 4.68μm (blue curve), in excellent agreement with the numerical simulation (green curve). To the best of our knowledge, the loss figures between 4.3 and 5.2μm represent the lowest thus far reported in a HCF [3,5-8]. In the 2nd AR window (~2.1-3.5μm) the simulation underestimates the measured loss; this is attributed to the optical launch exciting considerable HOM content. Strong water (~2.5-2.9μm) and CO_2 (~4.15-4.35μm) absorption features are seen in both lengths, resulting in an apparent narrowing of the 1st AR window in the 4.1m length; gas purging should however remove these features.

Fig. 1(b) shows transmission plots obtained at 0.40, 0.36, 0.32, and 0.28m bend diameters, these clearly show that the fiber is bend sensitive in both AR windows but remarkably even when coiled at a 0.32m diameter it still guides between 4.6-4.9μm, albeit with an additional ~2.2±0.6dB/m of loss. This is an extremely positive result, as a fiber with this structure (large core, large anti-resonant tube diameter, and low jacket glass thickness) would be anticipated to suffer from extreme bend sensitive and suggests a more optimal design may offer even lower bend sensitivity.

The cross-sectional SEM image inset in fig. 1(c) shows the high degree of structural uniformity achieved, in terms of the uniformity of the anti-resonant tubes diameter, 83.4±1.4μm (1.7%), thickness, 1.93±0.06μm (2.9%), and angular positioning, ±0.6º (1.2%), a key factor in the fiber's excellent optical performance.

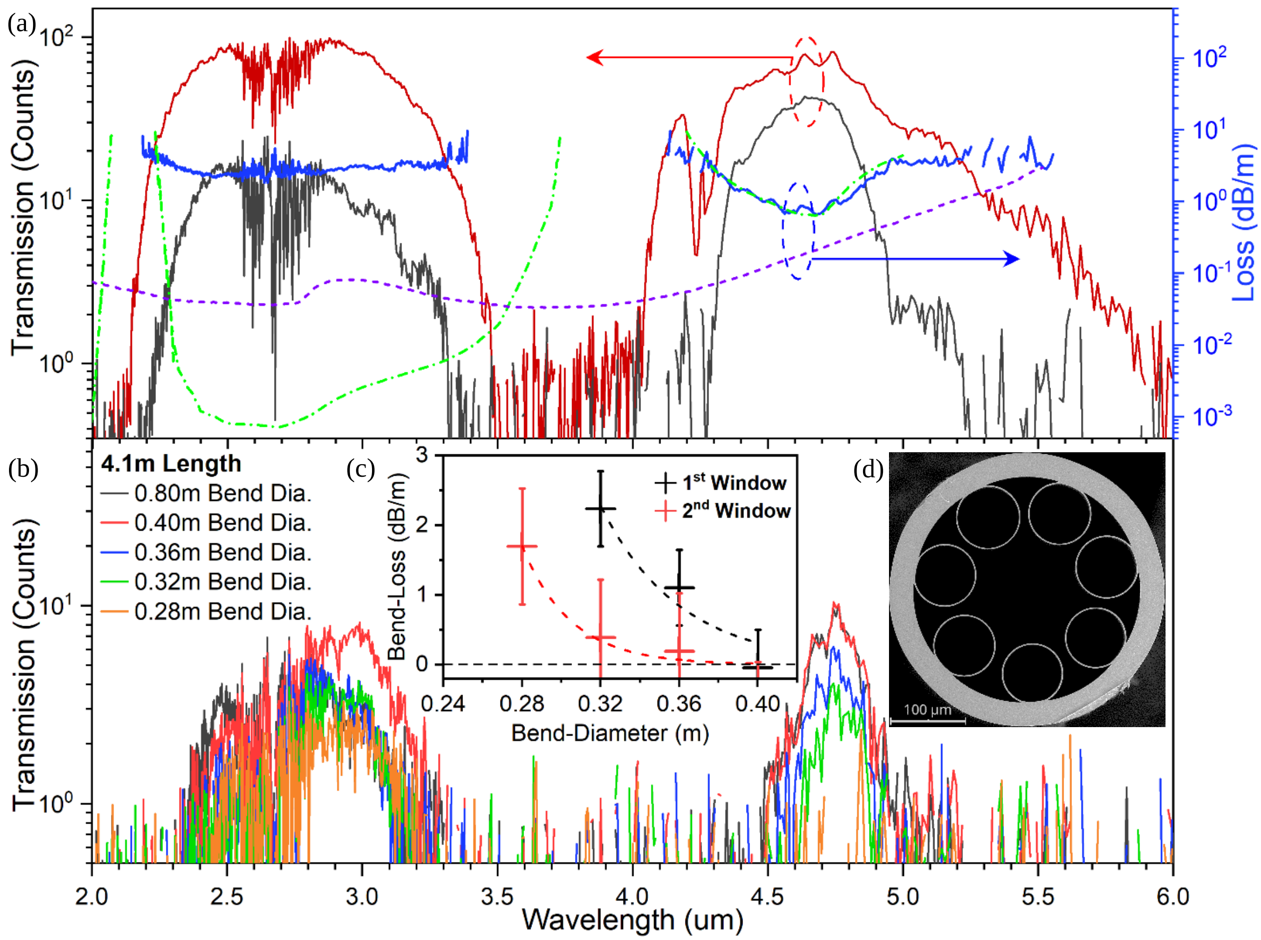

Fig.1. (a) Fiber transmission (dark grey – 4.1m, red – 1m) and loss (blue) plots for the reported fiber. The simulated loss of the fiber (based on modeling the inset SEM image (d), green dash-dotted curve) is also shown, along with the loss of a commercial 100μm core InF_3 fiber (purple dash curve [Thorlabs]) for comparison. (b) Transmission plots for various fiber bend diameters. (c) Bend-loss curves for the 1st and 2nd windows (d) An SEM image of the fiber cross-section.

The fabricated fiber has noticeable sensitivity to localized mechanical stress, as the use of tape (necessary to secure the fiber during bend-loss measurements) resulted in a reduction in the transmission (as can be seen by comparing the maximum counts in fig.1 (a) and (b)). This additional loss, in combination with the low signal level inherent with the characterization set-up used, makes quantifying the bend-loss challenging; as although the global behavior is as expected (loss increasing with decreasing bend diameter) individual wavelengths showed a variety of behaviors and loss gradients. However, the bend-loss has been estimated based on the average (over wavelength) transmission intensity at each bend diameter, see fig.1(c). Efforts are currently being made to fully investigate and understand this mechanical stress sensitivity, but it seems likely that it stems from the reduced jacket thickness.

4. Conclusion

We have reported a 132μm core, 358μm outer diameter single-ring anti-resonant silica fiber with record low propagation loss in the 4.3-5.2μm wavelength range, guidance between 4.0 and 5.9μm (through 1m, >0.8m bend diameter), and between 4.6-4.9μm when coiled at a 32cm diameter. This fibers performance suggests that the reduced jacket thickness approach employed has merit and a more optimized design may offer sufficiently low propagation and bend-loss for real-world usage, even at wavelengths that were believed inaccessible for silica fibers.

5. Acknowledgements

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6. References

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