Advances in Hollow Core Fiber for the 1µm and Visible Wavelength Regions

H. Sakr, Y. Chen, T. D. Bradley, G. T. Jasion, J. R. Hayes , I. A. Davidson, E. Numkam Fokoua, N. V. Wheeler, D. J. Richardson, and F. Poletti*

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, UK
*Corresponding author e-mail: *fp@soton.ac.uk*

Abstract: We report advances in Nested Antiresonant Nodeless hollow-core Fiber (NANF) operating in the visible and 1µm wavelength regions achieving record low optical losses of 2.8dB/km and 1.23dB/km at 650nm and 1070nm, respectively at these wavelengths.

OCIS codes: (060.2280) Fiber design and fabrication; (160.4760) Optical properties; (060.4005) Microstructured fibers

1. Introduction

Hollow core antiresonant fibers (HC-ARFs) are an emerging technology that offer the potential for low optical loss, low glass-mode overlap, high damage threshold, and a wide transmission bandwidth that can cover significant bandwidths in regions from the UV to the Mid-IR, and which can be optimized to work in the key 1µm and 1.55µm wavebands [1,2]. To date, several ARFs have been reported showing potential for power delivery and data transmission applications. Replacing the solid glass core of a conventional fiber with a vacuum or gas filled core of a hollow core fiber (HCF) can result in an ultralow nonlinear response and faster propagation speeds, enhancing their suitability for many applications. The optical properties of ARFs depend mainly on the arrangement and thickness of the core surrounding membranes, which should be optimized based on the operational wavelengths of interest.

Low optical loss in a 1µm-guiding HCF has been reported by various researchers including Maurel *et al.* [3] in a Kagome fiber showing 8.5dB/km loss at Nd-Yb:YAG laser wavelengths; Wheeler *et al.* [4] showing 12.3dB/km at 1010nm in a Kagome HCF; Chen *et al.* [5] showing 12.3dB/km at 1047nm in a 37-cell photonic bandgap fiber (PBGF); and Debord *et al.* [6] showing 8–20dB/km in the 800–1200nm region in tubular lattice HCF. The addition of smaller nested tubes to the widely known 'tubular' hollow core ARFs structure can considerably reduce their optical loss, allowing in principle a hollow core Nested Antiresonant Nodeless Fiber (NANF) to achieve total loss values lower than those of conventional solid fibers [7]. Since the introduction of the NANF concept, huge advancements at telecoms wavelengths have been achieved for both the optical loss [8,9] and operational bandwidth [10,11].

Recently we reported a NANF designed for the 1µm region with an optical loss of 2.78dB/km at 1070nm [12], ~3x lower loss than the lowest loss tubular ARF in the literature. In this work, we report improvement of the fiber structure in [12] resulting in a further reduction of 50% in the optical attenuation at 1µm relative to the current state-of-the-art. The fiber reported herein has a minimum loss of 1.23±0.03dB/km at both wavelengths 1070nm and 1100nm, to the best of our knowledge the lowest loss reported in an HCF at these wavelengths, and a loss below 3dB/km over a bandwidth of 278nm. Moreover, the fiber has an optical attenuation of 2.8dB/km at the wavelengths of 650nm and 680nm, lower than the current state-of the-art of 3.8dB/km at 680nm [13] and demonstrates the great progress being made in this short wavelength regime. These promising results leave significant margin for further improvements both in fiber loss and length.

2. Fabrication and characterization

Overall, the fabrication process of the fiber discussed here is similar to that reported in Sakr *et al.* [12]. The fiber is composed of 6 nested tubes fabricated in a two-stage stack and draw process supported by in-line fluid dynamics modelling to achieve the required antiresonant conditions [14]. The fiber has a total length of 823m, a core and a microstructured region diameter of 29.5±0.5µm and 79.5µm, respectively. The thickness of the six outer tubes, chosen to provide operation at 1060–1100nm in the second antiresonant window (2nd window), is 785±15nm, and of the inner tubes is 750±10nm. Small inter-tube azimuthal gaps ranging between 1.6-3.6µm were achieved throughout the fiber length. An SEM cross section of the fabricated fiber with an associated mode image is shown in Fig. 1(a). The main difference between the NANF reported here and that reported in [12] is the thickness of the glass cladding surrounding the microstructured region. Generally, for the NANF in [12], microbending was found to dominate the loss mechanism of the fiber in the 2nd window, which meant that further reduction in optical attenuation was possible simply by engineering the fiber to have a larger outer diameter [15], as shown to the inset of Fig. 1(b). The effect of this is clear on both the optical attenuation and the operational bandwidth of the fiber (Fig. 1(b)).

The cutback measurements were performed using a tungsten lamp white light source (WLS) and optical spectrum analyzer (OSA; AQ-6315A Yokogawa). Here the fibers were spooled on a 1-m circumference bobbin and a long length cutback was performed from 823m cut to 265m, while keeping the launch conditions contant. The fiber has a minimum loss of 1.23±0.03dB/km at both 1070nm and 1100nm wavelengths, the lowest loss reported in a HCF at these wavelengths to the best of our knowledge, and a loss below 3dB/km over a bandwidth of 278nm. A comparison between the current state-of-the-art with a loss of 2.78dB/km at 1070nm [12] and the fiber reported here is shown in Fig. 1(b) highlighting the increase in the operational bandwidth and the reduction in the optical loss. We have achieved a reduction of ~50% in the optical loss at 1070nm and an increase of ~50nm in the operational bandwidth.

Moreover, the reduction in the microbending loss in the fiber presented here compared to that in [12] has also improved the optical performance in the 3rd antiresonant window yielding a minimum loss of 2.8dB/km at wavelengths of 650nm and 680nm (Fig. 1(b)), again the lowest loss values reported in a HCF at these wavelengths to the best of our knowledge. Further improvements for 3rd window operation could be applied to reduce the loss further and increase the bandwidth.

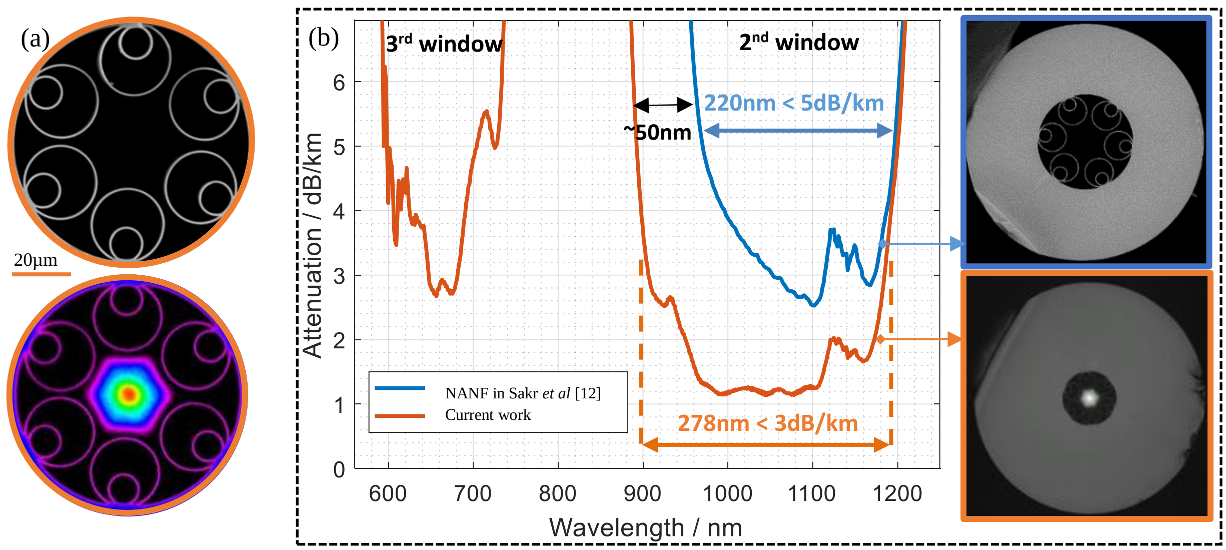

Fig. 1. (a) SEM and camera image of the guided mode of the fiber presented here (orange); (b) calculated cutback loss from 823m cut to 265m of the fiber reported here (orange curve), and comparison with current state-of-the-art [12] (blue curve). The insets in (b) show the difference in the glass diameter between the current work and the NANF reported in [12].

3. Conclusions

We report the fabrication of a NANF showing record low loss of 2.8dB/km and 1.23dB/km at 650nm and 1070nm, respectively, and with a length of 823m. By substantially increasing the outer glass diameter we have reduced the microbending sensitivity of the fiber and as a result have achieved a ~50% reduction in the total loss and an increase of 50nm in the operational bandwidth relative to the current state-of-the-art. Whilst these results are very encouraging we believe there remains significant scope for further improvements in both optical loss and fiber length.

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References

1. F. Poletti et al., "Towards high-capacity fibre-optic communications at the speed of light in vacuum," Nat. Photonics **7**, 279–284 (2013).
2. W. Belardi and J. C. Knight, "Hollow antiresonant fibers with low bending loss," Opt. Express **22**, 10091 (2014).
3. M. Maurel et al., "Optimized inhibited-coupling Kagome fibers at Yb-Nd : Yag (8.5 dB/km) and Ti:Sa (30 dB/km) ranges," Opt. Lett. **43**, 1598–1601 (2018).
4. N. V. Wheeler et al., "Low-loss Kagome hollow-core fibers operating from the near- to the mid-IR," Opt. Lett. **42**, (2017).
5. Y. Chen et al., "First demonstration of low loss, bend insensitive 37-cell Hollow-Core Photonic Bandgap Fiber at 1µm for High Power delivery applications," in *CLEO2016* (2016), Paper STu4P.1.
6. B. Debord et al., "Ultralow transmission loss in inhibited-coupling guiding hollow fibers," Optica **4**, 209–217 (2017).
7. F. Poletti, "Nested antiresonant nodeless hollow core fiber," Opt. Express **22**, 23807 (2014).
8. T. D. Bradley et al., "Record low-loss 1.3dB/km data transmitting antiresonant hollow core fibre," in *ECOC 2018* (2018).
9. T. D. Bradley et al., "Antiresonant hollow core fibre with 0.65 dB/km attenuation in the C and L telecommunication bands," in *ECOC 2019* (2019), PD.3.1.
10. H. Sakr et al., "Ultrawide bandwidth hollow core fiber for interband short reach data transmission," in *OFC* 2019 (2019), PDP Th4A.1.
11. H. Sakr et al., "Interband short reach data transmission in ultrawide bandwidth hollow core fiber," J. Light. Technol. **38**, 159–165 (2020).
12. H. Sakr *et al.*, "Record low loss hollow core fiber for the 1µm region," in *2019 (CLEO® / Europe-EQEC) , Munich 2019* (2019), Paper CE-5.5.
13. S. Gao *et al.*, "Hollow-core conjoined-tube negative-curvature fiber with loss approaching Rayleigh scattering limit of silica," in *CLEO 2019* (2019), STh1L.6.
14. G. T. Jasion *et al.*, "Fabrication of tubular anti-resonant hollow core fibers: modelling, draw dynamics and process optimization,"Opt. Express **27**, 20567 (2019).
15. B. D. Gloge, "Optical-fiber packaging and its influence on fiber straightness and loss," Bell Syst. Tech. J. **54**, 245–262 (1975).