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Low-loss micro-machining of anti-resonant hollow-core fiber with focused ion beam for optofluidic application

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Abstract: Hollow-core fiber (HCF) is a promising candidate for optofluidic applications because it can act as a gas-cell, permitting intense fluid-light interaction over extended lengths with low optical loss and inherent flexibility. Such a platform could pave the way for an all-fiberized, compact, robust and practical system for sensing applications. To facilitate this, we report a high-precision and repeatable micro-machining technique using focused ion beam (FIB) milling on a nodeless anti-resonant hollow-core fiber (ARHCF). Ga++ ions are bombarded on a 43 µm thick outer cladding of ARHCF for 30 minutes, to create a 50 µm deep fluidic channel, that has a negligible influence on the guiding properties of the fiber. The milled channel, followed by the 2.8 µm gap between adjacent 500 nm thin capillary tubes, provides direct access for liquid/gas to diffuse into the hollow-core region. The novel design presented here will allow ARHCFs to be spliced with solid-core fibers while preserving the fluidic channel. Corroborating results from simulation of such a structure are presented to demonstrate that no additional loss is induced by the milled hole.

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1. Introduction

Hollow-core fibers (HCFs) have been an active field of research in fields of high power lasers due to their high damage threshold and telecommunication due to their low latency [1]. Furthermore, they provide a promising platform for intense light-matter interaction due to the ability to confine most of the light within the small hollow core region with a scalable fiber length [2]. The first low-loss HCF had a photonic bandgap (PBG) structure [3], where the hollow core is surrounded by a periodic micro-structured cladding. The micro-structured cladding of a hollow core PBG (HCPBG) fiber is composed of holes that run through the bulk material (silica for example) and create a 2D crystal lattice that forbids certain frequencies from propagating through them. The light is therefore confined within the hollow core region and propagates along the fiber. The entire surrounding structure (cladding) is thus crucial for the guiding property of a HCPBG. This is important to mention because many attempts have been made to create micro-channels through the holey-cladding, in order to enhance the diffusion of fluids (i.e. liquid or gas) into the core of the fiber [4–7]. Micro-channels in HCFs are particularly necessary when such fibers are fusion-spliced to solid-core fibers [8,9] to make compact and robust sensors, because splicing blocks the access to the fiber core from the facet and prevents fluid diffusion between the fiber core and external environment. Such diffusion, however, is essential for many applications in gas-filled [5,10,11] or liquid-filled [12–14] HCF experiments, where interaction between liquid/gas with confined light is required. The creation of access channels into the core that can...
survive splicing and does not increase the insertion loss of the fiber by light leaking out of the core, is thus of prime importance for the use of HCFs in sensing applications.

The lowest loss induced by a micro-channel in an HCF reported in the literature is \( \sim 0.35 \text{ dB} \) for a single hole with a diameter of \( \sim 500 \text{ nm} \), drilled with femtosecond laser [4]. In another report with a similar technique, a hole size of \( 20 \mu\text{m} \) was shown to induce \( \sim 0.5 \text{ dB} \) loss per micro-channel in an HCF, under optimum conditions [6]. Other micro-fabrication techniques such as pressurized fusion splice method, results in an even higher loss of \( 6 \text{ dB} \) for a single hole of \( 64 \mu\text{m} \) wide [15]. All the aforementioned micro-channels are drilled in a HCPBG fiber, where loss induced by micro-defects in the fibers is almost inevitable due to the strong dependence of the guiding properties on the exact periodicity and symmetry of the PBG structure [16]. A relatively new type of HCF that has attracted significant interest in the HCF community is the anti-resonant HCF (ARHCF), because of its lower loss, single-modedness and broader transmission bandwidth when compared to hollow core PBG [1,17]. Furthermore, its simple structure significantly reduces fabrication complexity. In an ARHCF, light is guided in the fiber core region via the anti-resonant reflection optical waveguiding (ARROW) mechanism, which is achieved by surrounding the core region with a cladding made of single or multiple layers of capillary struts/tubes. The surrounding capillary tubes reflect light to the fiber core through ARROW mechanism, and they can either be touching [18,19] or non-touching [20,21] – also known as a nodeless tube lattice. The latter will be used in this work.

Recently, an ARHCF was spliced to a standard step-index single-mode fiber (SMF), with a splice loss of \( \sim 1.5 \text{ dB} \) [22] despite the high mode-mismatch between the \( 40 \mu\text{m} \) ARHCF and the \( 9 \mu\text{m} \) SMF. A significantly lower splice loss of \( 0.3 \text{ dB} \) has been demonstrated in HCPBG fibers with mode field diameter similar to SMF [23]. Despite improvements in the splicing of these fibers, the pertinent problem that arises from blocking access to the core remains a challenge. Femtosecond laser ablation technology has been used to drill micro-channel in ARHCF, inducing a relatively high loss of \( \sim 1 \text{ dB} \) per channel [24] due to damages to the capillaries. A very recent study has used femtosecond laser micromachining of smooth channels in ARHCFs to access the core of the fiber, achieving a big channel size of \( 150 \mu\text{m} \) with an induced loss of \( 0.45 \text{ dB} \) [25]. This is still higher than the \( 0.35 \text{ dB} \) loss reported in [4] although with a much larger hole size. In these reports, due to the geometry of the fibers and the lack of real-time imaging during micromachining, damage to the capillary elements of the fiber is almost inevitable, consequently inducing additional loss.

In this paper, we present a novel approach of using a well-known ion beam milling technique to create a channel between the adjacent capillaries of a nodeless ARHCF, to provide access for fluid transfer to the fiber core, even when the ARHCF is spliced to a solid-core SMF. This technique takes advantage of the capillary separation in nodeless ARHCF and the fact that the outer cladding region is not involved in the ARROW mechanism. Consequently, high precision ion beam milling could be used to drill micro-channels on the outer cladding, while the gap between the non-touching capillaries of the ARHCF serves as a natural aisle between the core region and the micro-channels. This minimizes or even completely eliminates additional loss as a result of the micro-machining, this is corroborated by numerical simulations.

2. Simulation of the milled structure on ARHCF

To demonstrate the effect, or lack thereof, of the optofluidic channel on the light confinement and loss of the ARHCF, the finite-element method was implemented using a commercial software (COMSOL). A micro-channel, positioned in the outer cladding between two non-touching capillaries, will allow access of fluids to the fiber core. The ARHCF used for this work has seven non-touching capillaries, as shown in the scanning electron microscopy (SEM) in Fig. 1(a). We design two micro-channels, depicted in Fig. 1(c) with similar fiber dimensions for the simulation. As mentioned earlier, the ARROW depends only on the design and geometry of
the inner capillaries. The simulation was run for two models, first for a non-machined fiber, shown in Fig. 1(b), and second for fiber with two channels, shown in Fig. 1(c). The models are designed using dimensions from SEM image in Fig. 1(a). A perfectly matched layer is used as the boundary condition. A fine mesh size ranging from $\lambda/6$ to $\lambda/4$ is adopted for all the geometry regions (includes air core, silica cladding, and PML), to ensure simulation accuracy.

**Fig. 1.** (a) Scanning electron microscope (SEM) image of ARHCF facet, a magnified section of the non-touching capillary is shown below (a). Design of ARHCF for simulation in COMSOL with and without micro-channels in (b) and (c), respectively. The light-blue part donates the air region, and the grey part donates the silica part.

In the model, surface scattering loss was ignored because the inner surface roughness of the waveguide is much smaller than the laser wavelength in the infrared region [20] and also due to the large core diameter of the ARHCF [20]. Here, the core diameter of the fiber is 46 $\mu$m, as shown by the SEM in Fig. 1(a). The geometry profile of the fiber is built in 2D space, as shown in Fig. 1(b) and 1(c). The design in Fig. 1(c) with two channels in the outside silica cladding part indicates that the fiber in 3D space has two long slits of 30 $\mu$m x 43 $\mu$m along its axial direction, which has a much larger core-exposed area than the experimental case where only two slits of 50 $\mu$m depth.

Even with such long slits, the simulation results in Fig. 2 show that the fiber loss of machined fiber remains unchanged compared to the fiber without channels, suggesting that altering the outside silica cladding part has little to no impact on the optical performance of the anti-resonant fiber, which is consistent with the conclusion in Ref. [26]. As a result, the fundamental mode for the two separate cases also have the same distribution and diameter, as indicated by Fig. 2(b) and 2(c). The loss profiles in Fig. 2(a) shows a perfect overlap between the two-loss profiles, with a high loss at $\sim 1.25\mu$m due to the fiber resonance. The fiber loss for both designs gradually increases towards the longer wavelength due to the increased material loss of silica and overlap with the fundamental mode at that wavelength. A weak bump around 2.9 $\mu$m is due to an absorption peak of the silica material in this spectral region [27].
3. Fabrication and FIB micromachining

The ARHCF is fabricated through the well-known stack and draw technique, where seven silica tubes are stacked in a larger silica tube with a broader inner diameter, forming the final preform. The preform is put in the furnace and heated above the glass transition temperature of silica, under controlled pressures in core and inner capillary regions, to prevent hole-collapsing. The detailed fabrication process is presented elsewhere [28]. FIB is an advanced and versatile technique for milling and sputtering of materials. It allows direct patterning on a sample through the bombardment of ions on the sample. Unlike laser ablation, the area of interest is predefined, as shown in Fig. 3(b) and accurately controlled throughout the milling process. The technique involves dual-beam instruments containing an SEM imaging system, and an FIB gun that sends highly energetic ions, such as gallium ion (Ga⁺) beam. Ga⁺ is preferred because it has a low melting point and vapor pressure, which simplifies operations [29]. The main advantage of FIB is its high alignment precision, in that it can mill spot sizes less than 10 nm [30]. Similar to scanning electron microscopy, in FIB, highly energetic electrons can accumulate on insulating surfaces. Therefore, coating of fiber with a conductive materials is necessary to reduce surface charging and allow high magnification levels. These electron charges can cause random deflection of the incident ion beam and thus damage the milling profile.

The sample was prepared by stripping the polymer coating from the fiber tip and cleaving the fiber with tension cleaver to get a flat end facet. To minimize the charging effect, the fiber is coated with a 5 nm layer of gold using sputter coater (Cressington, model 208HR, targets: Au/Cr). Moreover, the fiber is fixed on top of conductive carbon tape attached to a grounded sample holder, shown in Fig. 3(a). Additional carbon tape is used to fix the fiber in place. The fiber is then placed in the FIB system (FEI Quanta 200 3D SEM-FIB), with the tip aligned at high incident angle (≈90°) between the surface normal and the FIB gun. This significantly increases the milling rate, since the FIB sputtering yield roughly increases with 1/|cos(θ)| [32,33], where θ here is the angle between the fiber-facet normal and direction of the FIB gun. The milling procedure is performed with an acceleration voltage of 30 kV and current of 20 nA. This high ion current leads to a high milling rate, a channel of 50 µm depth takes ~30 minutes.

The experimental demonstration of two fluidic micro-channels is presented in Fig. 4(b) and 4(c). Two 43 µm x 30 µm channels of ~50 µm deep were milled adjacent to the gap between two
Fig. 3. (a) Coated ARHCF mounted on SEM holder. (b) ARHCF facet, with pink section showing the area to be milled. (c) SEM image of 1st milled channel. The bottom image shows lateral image of milled fiber. The non-symmetry of fiber facets in lateral images is an artefact due to angle-correction in SEM image reconstruction, details of this can be found in Ref. [31].

capillaries. Figure 4(a) shows the fiber before milling, and Fig (b) and (c) are the lateral and cross-section of the milled fiber, respectively.

Fig. 4. (a) ARHCF before milling. (b) Milled facet of ARHCF, two adjacent channels are milled with depth of $\sim 50 \mu m$. (c) SEM image of fiber cross-section after milling. Two channels of 43 $\mu m$ x 30 $\mu m$ were achieved.

4. Conclusion

In this paper, we discuss the use of FIB milling on nodeless ARHCF and we showed how micro-channels can be achieved on the fiber facets without damaging the cladding capillaries, thus resulting in nearly zero loss as a result of the micromachining. This design will allow access for gas/liquid to the cores even after the facet is spliced with a solid core fiber. Since the many applications of an HCF with low loss channels is obvious and has already been demonstrated in several papers [4,6,33–37], here we focus on the fabrication approach rather than specific sensing applications. The presented work is an additional step towards achieving an all-fiberized, low-loss fiber gas-cell for optofluidic applications.

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References

1. G. T. Jasion, T. D. Bradley, K. Harrington, H. Sakr, Y. Chen, Y. Chen, E. N. Fokoua, I. A. Davidson, A. Taranta, J. R. Hayes, D. J. Richardson, and F. Poletti, “Hollow Core NANF with 0.28 dB/km Attenuation in the C and L Bands,” in Optical Fiber Communication Conference Postdeadline Papers 2020 (2020), Paper Th4B.4 (Optical Society of America, 2020), p. Th4B.4.

2. A. I. Adamu, “Gas-filled Hollow-Core Photonic Crystal Fibers for sensing applications and ultrafast non-linear optics,” (2020).

3. R. P. Cregan, B. J. Mangan, J. C. Knight, T. A. Birks, P. S. J. Russell, P. J. Roberts, and D. C. Allan, “Single-Mode Photonic Band Gap Guidance of Light in Air,” Science 285(5433), 1537–1539 (1999).

4. C. J. Hensley, D. H. Broaddus, C. B. Schaffer, and A. L. Gaeta, “Photonic band-gap fiber gas cell fabricated using femtosecond micromachining,” Opt. Express 15(11), 6690–6695 (2007).

5. W. Jin, H. F. Xuan, and H. L. Ho, “Sensing with hollow-core photonic bandgap fibers,” Meas. Sci. Technol. 21(9), 094014 (2010).

6. A. van Brakel, C. Grivas, M. N. Petrovich, and D. J. Richardson, “Micro-channels machined in microstructured optical fibers by femtosecond laser,” Opt. Express 18(14), 8731–8736 (2007).

7. C. Markos, J. C. Travers, A. Abdolvand, B. J. Eggleton, and O. Bang, “Hybrid photonic-crystal fiber,” Rev. Mod. Phys. 89(4), 045003 (2017).

8. H. Y. Tam, “Simple fusion splicing technique for reducing splicing loss between standard singlemode fibres and erbium-doped fibre,” Electron. Lett. 27(17), 1597–1599 (1991).

9. F. County, F. Benabid, and P. S. Light, “Reduction of Fresnel back-reflection at splice interface between hollow core PCF and Single-Mode Fiber,” IEEE Photonics Technol. Lett. 19(13), 1020–1022 (2007).

10. R. M. Wynne, B. Barabadi, K. J. Creedon, and A. Ortega, “Sub-Minute Response Time of a Hollow-Core Photonic Bandgap Fiber Gas Sensor,” J. Lightwave Technol. 27(11), 1590–1596 (2009).

11. A. I. Adamu, F. E. Ozturk, and M. Bayindir, “Binary coded identification of industrial chemical vapors with an optofluvic nose,” Appl. Opt. 55(36), 10247–10254 (2016).

12. F. M. Cox, A. Argyros, and M. C. J. Large, “Liquid-filled hollow core microstructured polymer optical fiber,” Opt. Express 14(9), 4135–4140 (2006).

13. W. Qian, C.-L. Zhao, Y. Wang, C. C. Chan, S. Liu, and W. Jin, “Partially liquid-filled hollow-core photonic crystal fiber polarizer,” Opt. Lett. 36(16), 3296–3298 (2011).

14. R. Zeltner, D. S. Bykov, S. Xie, T. G. Euser, and P. St. J. Russell, “Fluorescence-based remote irradiation sensor in liquid-filled hollow-core photonic crystal fiber,” Appl. Phys. Lett. 108(23), 231107 (2016).

15. C. M. B. Cordeiro, E. M. dos Santos, C. H. B. Cruz, C. J. S. de Matos, and D. S. Ferreira, “Lateral access to the holes of photonic crystal fibers – selective filling and sensing applications,” Opt. Express 14(18), 8403–8412 (2006).

16. E. N. Fokoua, D. J. Richardson, and F. Poletti, “Impact of structural distortions on the performance of hollow-core photonic bandgap fibers,” Opt. Express 22(3), 2735–2744 (2014).

17. H. Sakr, Y. Chen, T. Bradley, G. Jasion, J. R. Hayes, I. Davidson, E. Numkam Fokoua, N. Wheeler, D. Richardson, and F. Poletti, “Advances in hollow core fiber for the 1µm and visible wavelength regions,” in (2020), p. paper: SoW1H.5.

18. F. Yu, W. J. Wadsworth, and J. C. Knight, “Low loss silica hollow core fibers for 3–4 µm spectral region,” Opt. Express 20(10), 11153–11158 (2012).

19. F. Poletti, J. R. Hayes, and D. J. Richardson, “Optimising the Performances of Hollow Antiresonant Fibres,” in 37th European Conference and Exposition on Optical Communications (2011), Paper Mo.2.LeCervin.2 (Optical Society of America, 2011), p. Mo.2.LeCervin.2.

20. F. Poletti, “Nested antiresonant nodeless hollow core fiber,” Opt. Express 22(20), 23807–23828 (2014).

21. A. N. Kolyadin, A. F. Kosolapov, A. D. Pryamikov, A. S. Briukov, V. G. Plotnichenko, and E. M. Dianov, “Light transmission in negative curvature hollow core fiber in extremely high material loss region,” Opt. Express 21(8), 9514–9519 (2013).

22. Y. Min, A. Filipkowski, G. Stępniowski, M. Klimeczak, L. Zhao, and R. Buczyński, “Fusion splicing and termination of silica hollow core anti-resonant fibers with single mode fibers,” in Conference Programme (n.d.), p. 88.

23. R. Thapa, K. Knabe, K. L. Corwin, and B. R. Washburn, “Arc fusion splicing of hollow-core photonic bandgap fibers for gas-filled fiber cells,” Opt. Express 14(21), 9576–9583 (2006).

24. M. Hou, F. Zhu, Y. Wang, Y. Wang, C. Liao, S. Liu, and P. Lu, “Antiresonant reflecting guidance mechanism in hollow-core fiber for gas pressure sensing,” Opt. Express 24(24), 27890–27898 (2016).

25. C. C. Novo, D. Choudhury, B. Siwicki, R. R. Thomson, and J. D. Shephard, “Femtosecond laser machining of hollow-core negative curvature fibres,” Opt. Express 28(17), 25491–25501 (2020).

26. P. Song, P. Song, K. Y. Phoong, and D. Bird, “Quantitative analysis of anti-resonance in single-ring, hollow-core fibres,” Opt. Express 27(20), 27745–27760 (2019).

27. S. T. Yang, M. J. Matthews, S. Elhadj, D. Cooke, G. M. Guss, V. G. Draggoo, and P. J. Wegner, “Comparing the use of mid-infrared versus far-infrared lasers for mitigating damage growth on fused silica,” Appl. Opt. 49(14), 2606–2616 (2010).

28. I. E. Antonio-Lopez, S. Habib, A. V. Newkirk, G. Lopez-Galmiche, Z. S. Eznaveh, J. C. Alvarado-Zacarias, O. Bang, M. Bache, A. Schulzgen, and R. A. Correa, “Antiresonant hollow core fiber with seven nested capillaries,” in 2016 IEEE Photonics Conference (IPC), pp. 402–403.
29. Y. Fu, “Integration of microdiffractive lens with continuous relief with vertical-cavity surface-emitting lasers using focused ion beam direct milling,” IEEE Photonics Technol. Lett. 13(5), 424–426 (2001).
30. N.-T. Nguyen, Micromixers: Fundamentals, Design and Fabrication (William Andrew, 2011).
31. P. Jin and X. Li, “Correction of image drift and distortion in a scanning electron microscopy,” J. Microsc. 260(3), 268–280 (2015).
32. S. Reyntjens and R. Puers, “A review of focused ion beam applications in microsystem technology,” J. Micromech. Microeng. 11(4), 287–300 (2001).
33. W. Yuan, F. Wang, A. Savenko, D. H. Petersen, and O. Bang, “Note: Optical fiber milled by focused ion beam and its application for Fabry-Pérot refractive index sensor,” Rev. Sci. Instrum. 82(7), 076103 (2011).
34. A. I. Adamu, M. K. Dasa, O. Bang, and C. Markos, “Multispecies Continuous Gas Detection With Supercontinuum Laser at Telecommunication Wavelength,” IEEE Sens. J. 20(18), 10591–10597 (2020).
35. M. Nikodem, G. Gomółka, M. Klimczak, D. Pysz, R. Buczyński, and R. Buczyński, “Demonstration of mid-infrared gas sensing using an anti-resonant hollow core fiber and a quantum cascade laser,” Opt. Express 27(25), 36350–36357 (2019).
36. N. M. Litchinitser and E. Poliakov, “Antiresonant guiding microstructured optical fibers for sensing applications,” Appl. Phys. B 81(2-3), 347–351 (2005).
37. H. Gao, Y. Jiang, L. Zhang, Y. Cui, Y. Jiang, J. Jia, and L. Jiang, “Antiresonant mechanism based self-temperature-calibrated fiber optic Fabry–Perot gas pressure sensors,” Opt. Express 27(16), 22181–22189 (2019).