Laser-assisted lateral optical fiber processing for selective infiltration

Betty Meng Zhang,[1] Yicheng Lai,[2] Wu Yuan,[3,4] Yen Peng Seah,[4] Perry Ping Shum,[1,*] Xia Yu,[4] and Huifeng Wei[5]

[1]*School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore*
[2]*Data Storage Institute, 5 Engineering Drive 1, Singapore 117608, Singapore*
[3]*Department of Biomedical Engineering, Johns Hopkins University, Baltimore, MD 21205, USA*
[4]*Singapore Institute of Manufacturing Technology, 71 Nanyang Drive, Singapore 638075, Singapore*
[5]*Yangtze Optical Fiber and Cable Company Ltd. R&D center, Wuhan 430073, China*
[*]*shum@ieee.org*

Abstract: We propose a new technique to perform precise selective infiltration of an air hole in the photonic crystal fiber (PCF). To carry out the infiltration process, the end face of the PCF is covered by a mask, which is fabricated by femtosecond laser inscription from the lateral direction. This proposed method overcomes the conventional limitation of maximum mask thickness. An analytical model is further proposed and demonstrated accurate determinations of the fabricated channel diameter in the mask.

OCIS codes: (060.4005) Microstructured fibers; (060.2310) Fiber optics; (060.2280) Fiber design and fabrication; (060.2340) Fiber optics components; (060.5295) Photonic crystal fibers; (060.7140) Ultrafast processes in fibers.

References and links

1. F. Wang, W. Yuan, O. Hansen, and O. Bang, "Selective filling of photonic crystal fibers using focused ion beam milled microchannels," Opt. Express **19**(18), 17585–17590 (2011).
2. B. Eggleton, C. Kerbage, P. Westbrook, R. Windeler, and A. Hale, "Microstructured optical fiber devices," Opt. Express **9**(13), 698–713 (2001).
3. F. Benabid, F. Couny, J. C. Knight, T. A. Birks, and P. St. J. Russell, "Compact, stable and efficient all-fibre gas cells using hollow-core photonic crystal fibres," Nature **434**(7032), 488–491 (2005).
4. B. T. Kuhlmey, B. J. Eggleton, and D. K. C. Wu, "Fluid-filled solid-core photonic bandgap fibers," J. Lightwave Technol. **27**(11), 1617–1630 (2009).
5. M. Skorobogatiy, K. Saitoh, and M. Koshiba, "Transverse light guides in microstructured optical fibers," Opt. Lett. **31**(3), 314–316 (2006).
6. M. Vieweg, S. Pricking, T. Gissibl, Y. V. Kartashov, L. Torner, and H. Giessen, "Tunable ultrafast nonlinear optofluidic coupler," Opt. Lett. **37**(6), 1058–1060 (2012).
7. S. Zhang, X. Yu, Y. Zhang, P. Shum, Y. Zhang, L. Xia, and D. Liu, "Theoretical study of dual-core photonic crystal fibers with metal wire," IEEE Photonics J. **4**(4), 1178–1187 (2012).
8. Y. Huang, Y. Xu, and A. Yariv, "Fabrication of functional microstructured optical fibers through a selective-filling technique," Appl. Phys. Lett. **85**(22), 5182–5184 (2004).
9. L. Xiao, W. Jin, M. Demokan, H. Ho, Y. Hoo, and C. Zhao, "Fabrication of selective injection microstructured optical fibers with a conventional fusion splicer," Opt. Express **13**(22), 9014–9022 (2005).
10. C. Martelli, J. Canning, K. Lyytikainen, and N. Groothoff, "Water-core Fresnel fiber," Opt. Express **13**(10), 3890–3895 (2005).
11. 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).
12. Y. Wang, C. R. Liao, and D. N. Wang, "Femtosecond laser-assisted selective infiltration of microstructured optical fibers," Opt. Express **18**(17), 18056–18060 (2010).
13. K. Zhou, Y. Lai, X. Chen, K. Sugden, L. Zhang, and I. Bennion, "A refractometer based on a micro-slot in a fiber Bragg grating formed by chemically assisted femtosecond laser processing," Opt. Express **15**(24), 15848–15853 (2007).

1. Introduction

Selective infiltration of air holes in photonic crystal fibers (PCFs) with functional materials receives increasing interest these days. It tailors the light guiding in PCFs through the desired material properties, and leads to optical fiber devices with advanced functions [1], such as hybrid guiding [2], high nonlinearity [3], tunable transmission and dispersion [4], etc. This facilitates the high-level integration of optical functionalities into the fiber devices which is in line with the latest trend in the development of all fiber devices [5].

One of the functional devices achievable by this technique is ultrafast nonlinear coupler [6], which can be made based on a dual-core PCF (DC-PCF). Controllable directional power transfer occurs between the two closely placed solid cores of DC-PCF. If the central air hole is filled with metal, the coupling efficiency of the DC-PCF could be increased up to 81.82% owing to the resonance between fiber core-guided modes and metal wire plasmonic mode [7]. In addition, the coupling loss, the insertion loss, and the extinction ratio of such fiber coupler can also be optimized via the proper design of fiber structural parameters and the proper choice of the functional materials. Such compact fiber coupler has the potential to be used in many optical communication devices.

Various selective infiltration techniques for PCFs have been demonstrated before. One method is manual gluing [4], which uses the glue to block all the air holes except the ones to be filled with the functional material. The entire air holes blocking process is controlled manually with the aid of translational stage, microscope and charge-coupled device camera. Another technique is using the injection-cleaving process [8], which exploits differential filling speeds of different sized air holes inside PCFs. However, only PCFs with sufficiently large air hole size variations can be infiltrated with this method. An alternative method is to selectively collapse the cladding air holes in PCFs using the arc discharge in the conventional fusion splicer while leaving the central hole open [9]. This technique is only applicable for the hollow core PCFs. Splicing the PCF with a single air hole hollow core fiber as a guiding channel has also been demonstrated [10]. This technique requires a hollow core fiber with a compatible dimension and only works for the selective infiltration of the central air hole.

It has also been proposed to use the focused ion beam (FIB) micromachining [11], during which sufficient energy transfers from accelerated ions to chemically bonded atoms and enable the atoms to overcome the binding energy and material work function. However, this process can be limited by ion beam deflection due to charge accumulation on the fiber dielectric surface, compromising the achievable milling profile [1]. In addition, such micromachining process can be time-consuming.

To exploit the spatial precision of ultrafast laser processing technology, femtosecond laser micromachining has been demonstrated to achieve selective infiltration of PCF. Past report highlighted drilling from the end face of a SMF to make a guiding channel connecting to the desired air holes of the PCF [12]. Compared to the FIB, this technique circumvents random deflection of the incident beam caused by backscattered and sputtered ion emissions, and reduces the operation cost for the process. Splicing the PCF uniformly with a SMF seals all the surrounding air holes firmly, which allows reliable infiltration for various types of functional materials even under high pressure. Moreover, with a melting temperature above 1200°C, the silica SMF-mask is able to endure very high working temperature. However, end-facet micro-machining of SMF-mask can limit the aspect ratio of the micro-channel achievable. High precision cleaving is required to produce ultra-thin (10 μm) SMF-mask to facilitate both the laser micromachining as well as the beam positioning processes [12]. If only a normal fiber cleaver is used to prepare the mask, without the help of high magnification long-working-distance microscope, the thickness of the mask can hardly be less than 100μm. Achievable micro-channel through mask of thickness over 100 μm can exceed PCF narrow air hole diameter (in the range of 2 μm), and the process poses alignment challenges to steer clear of air holes in close proximity (~1 μm) for PCF with tight pitches.

In this paper, we propose and demonstrate a versatile selective infiltration technique. A micro-channel is fabricated on the SMF-mask by lateral femtosecond laser inscription and successive controllable HF etching. By processing the fiber from the side, our method overcomes the limitation of aspect ratio and is able to obtain inscription length as long as the moving range of the translation stage. No high precision laser cleaving is required. The analytical model further proposed facilitates accurate determination of the fabricated channel diameter within the SMF mask. We have successfully infiltrated the functional material to the PCF center air hole with a diameter of 2.5 μm while all the surrounding air holes, with the nearest ones only 1.25 μm away, are completely untouched. Our method has the potential to infiltrate to an even smaller air hole in the PCF under high temperature and high pressure, which allows the realization of more compact and complicated PCF-based functional devices.

2. Method

The proposed method for the femtosecond laser-assisted selective infiltration of a PCF consists of three steps:

a) Fiber mask preparation

The target PCF is first spliced with a standard SMF. A transition region between SMF and PCF is formed after fusion splicing, as shown in Figs. 1(a) and 1(b). In the transition region, all the holes in PCF are collapsed due to the long arc duration in the splicing process. This transition region covers the cross section of the PCF and will function as a fiber mask.

b) Femtosecond laser inscription and micro-channel etching

A femtosecond laser at 800 nm is then used to inscribe within the transition region along its axis, as shown in Fig. 1(c). It is usually difficult to focus the laser at the central air hole from the side of a PCF, because the cladding air holes distort both the imaging and the laser beam. Our method overcomes this problem by splicing the target PCF concentrically with a reference SMF. The laser beam is first focused at the SMF core, which is much easier and has been commonly carried out for fiber Bragg grating fabrication, and then moved horizontally along the fiber towards the PCF. After inscription, the SMF and left part of the transition region is removed by using a fiber cleaver, as shown in Fig. 1(d). HF is then used to etch out a micro-channel towards the PCF, as shown in Fig. 1(e). The etching rate in the laser inscribed region is much faster than the pristine fiber. By controlling the etching time, a hole with desired diameter can be obtained. This forms a fiber mask with a micro-channel connecting to the central air hole of the PCF and covering the surrounding cladding air holes.

c) Functional material infiltration

Vacuum cleaning process is applied to remove the HF and residuals in the micro-channel. Then functional material can be infiltrated into the desired PCF center hole by using the capillary effect, as shown in Fig. 1(f). Since the rest of the holes of PCF are all covered by the fiber mask, none of them will be infiltrated. After infiltration, the fiber mask together with micro-channel is removed by a fiber cleaver to obtain an ideal PCF end face, as shown in Fig. 1(g). Successive procedures will be needed for long-time preservation of the infiltrated gas or liquid inside the air hole, so as to fabricate a practical fiber device. As for our case, the infiltrated liquid can be held by the capillary effect long enough until we finish all the observations.

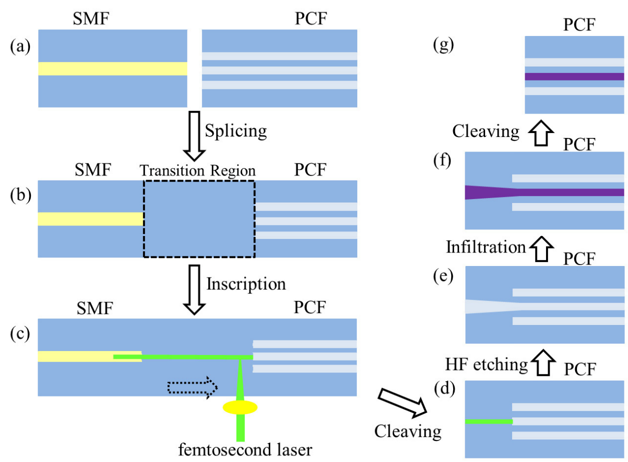

Fig. 1. Detailed steps of the proposed method.

3. Experiment

A DC-PCF is used in the experiment, which has an air hole diameter of 2.5 μm and a pitch size of 3.75 μm. A standard SMF is spliced with the PCF using Fitel S175 V2000 Fusion Splicer under manual mode. The splicing parameters are 100 ms cleaning, 120 ms pre-fuse, and 4000 ms 200 V arc. After splicing, a transition region with ~451 μm length can be clearly observed under the microscope, as shown in Fig. 2(a). The core of SMF on the left-hand side and the PCF air hole bundles on the right-hand side can also be seen.

The spliced fiber is held horizontally on a cover slip placed on a translation stage. The transition region of the spliced fiber is immersed in the index matching oil to mitigate the beam profile distortion of the focused laser beam, as illustrated in Fig. 3. The femtosecond laser beam is incident from the bottom through an objective lens. Instead of moving the focal point of the laser beam, the fiber together with the cover slip is moved by the translation stage at a speed of 50 μm/s. The inset of Fig. 3 shows the image of the fiber sample during the inscription. The femtosecond laser pulse with a pulse width of 150 fs, a pulse energy of 80 nJ and a repetition rate of 100 kHz is employed. The inscribed region is shown in Fig. 2(b).

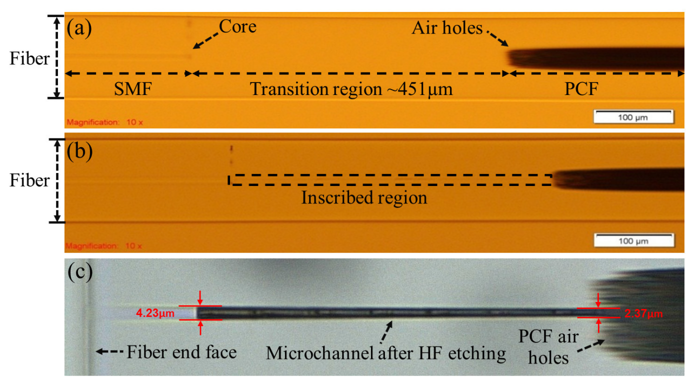

Fig. 2. Magnified microscope images of the PCF spliced with SMF. (a) The fiber sample after splicing. (b) The fiber sample after femtosecond laser inscription. (c) The fiber sample after HF etching.

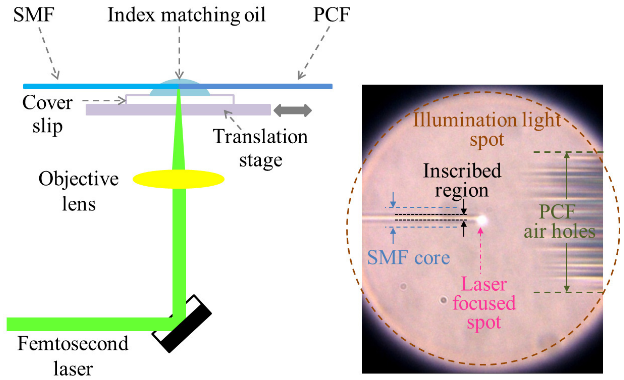

Fig. 3. Schematic of the femtosecond laser inscription on the transition region of the spliced fiber sample.

After the femtosecond laser inscription process, the fiber is cleaned and cleaved at the SMF side, 185.63μm away from the air holes in PCF. Then the HF solution with a volume ratio of 8% is used to etch away the inscribed region to form a micro-channel towards the PCF. The PCF and HF liquid are put in a Teflon container and stirred by an ultrasonic to speed up the etching process. The micro-channel has a cone shape with the narrow side pointing at the PCF. With accurate etching time estimated by our analytical model, a fiber mask attached to the PCF end face is fabricated. As shown in Fig. 2(c), the micro-channel has a diameter of 2.37μm when it reaches the PCF, which is very close to the desired hole diameter of 2.5μm.

Finally, the functional material is infiltrated into the central air hole of the PCF through the micro-channel. For a proof-of-concept demonstration we use index matching oil as the functional material here. After the infiltration process and the successive cleaving, an ideal PCF end face can be observed using an inverted microscope. As shown in Fig. 4(a), the central air hole of the PCF is filled with the index oil while the surrounding air holes are completely untouched. Note that the pitch size of the PCF is 3.75μm and the air hole diameter is 2.5μm which means the edge to edge distance between two adjacent air holes is only 1.25μm. To further explore and confirm the feasibility of this method, we have also infiltrated an air hole in the second ring, as shown in Fig. 4(b). Simply by changing the focal depth of the laser beam, this technique can be applied to infiltrate air holes in other rings as well.

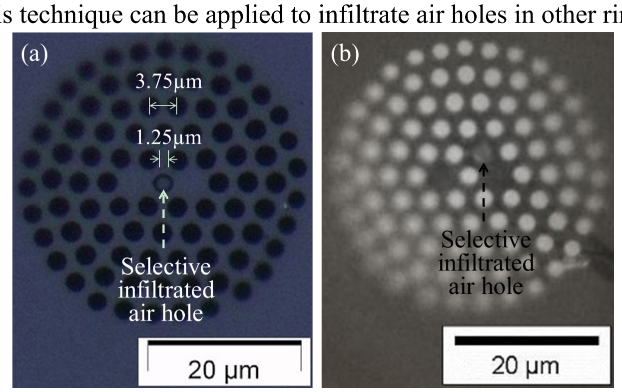

Fig. 4. Magnified microscope images of the cross-section of the PCFs with single air hole in (a) the first ring and (b) the second ring selectively infiltrated.

4. Analysis of micro-channel etching

The etching speed in the femtosecond laser-inscribed region is 100 times faster than that in the pristine region [13]. Hence the micro-channel with a cone-shape formed by HF etching is guided by the inscribed region, as shown in Fig. 5(a). To give a good estimation of the required etching time, the etching process is modeled as follows:

When the cone-shape micro-channel opening extends to the PCF, the narrow side of it is embedded in the PCF air hole bundles and the exact etching depth cannot be measured. What available are the desired air hole diameter $\Phi' = 2.5$ μm when micro-channel reaches PCF and the distance h between the PCF end face and the fiber mask end face. A schematic diagram is shown in Fig. 5(b) where the dark red region on the left-hand side represents the hole bundles in PCF and the depth of micro-channel h' in this region is unknown in the actual measurement.

The etching speed is known to decrease as the etching depth increases [13]. For simplicity, in our case we define the etching speed as the movement speed of the cross section of micro-channel where its diameter equals to the desired diameter $\Phi' = 2.5$ μm. The required etching time is the time when the 2.5-μm-diameter cross section of the micro-channel moves by a length of h. The etching speed $v_{etching}$, can be modeled as $v_{etching} = v_0 - at$, where v_0 is the initial etching speed and acceleration a represents the decrease of the speed with time (and etching depth). The etching depth after time t is then given by $h = v_0 t - \frac{1}{2}at^2$. To find out the values of v_0 and a, etching experiments are performed on two SMF samples with different etching time, as shown in Figs. 5(c) and 5(d). With the measured etching depths $h + h'$ and the diameters of the opening Φ, we obtain $h = 10.19356t - 0.0478t^2$.

With the measured h, required etching time t can be obtained. In our case, the distance between the PCF end face and fiber mask end face is measured to be 185.63 μm, so the required etching time is 20.1 minutes. As shown in Fig. 2(c), the obtained air hole is with a diameter of 2.37μm at the PCF end face, which is very close to the desired size.

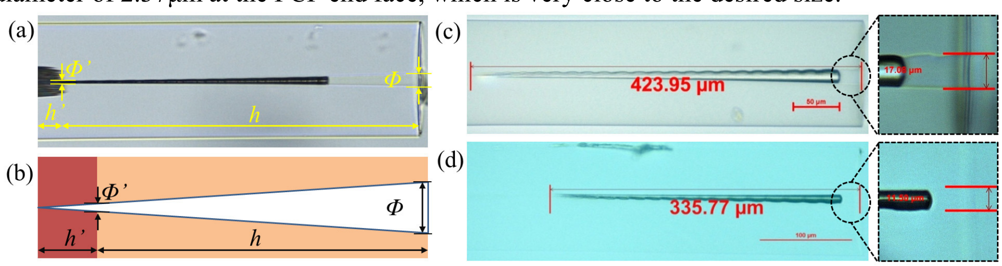

Fig. 5. Side view of etched fibers. (a) Image of the fiber sample under microscope. (b) Schematic drawing for modeling. (c) SMF Sample 1. (d) SMF Sample 2.

5. Conclusions

In conclusion, we proposed and demonstrated a practical, repeatable and accurate technique for precise selective infiltration of PCFs by harnessing the lateral femtosecond laser-assisted fiber processing. Using this method, we precisely infiltrate an air hole in photonic crystal fiber (PCF), with a small diameter of 2.5 μm and an ultra-short edge-to-edge air hole distance of 1.25 μm. Our proposed technique allows user to fabricate fiber mask with no limitation on thickness and precise micro-channel extended to the desired air hole in the PCF. This technique is also able to work in very high temperature and pressure which can facilitate the fabrication of various functional PCF-based devices.

Acknowledgment

We wish to acknowledge the funding for this project from Nanyang Technological University under the Undergraduate Research Experience on CAmpus (URECA) programme.