Femtosecond laser-assisted selective infiltration of microstructured optical fibers

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Abstract: A new method of selectively infiltrating microstructured optical fibers with the assistance of femtosecond laser micromachining is presented. With this technique, any type of air-holes in the cross-section of the microstructured optical fibers can be selectively infiltrated with liquids, which opens up a highly efficient, precise, flexible and reliable way of selective infiltrating and has high potential in the fabrication of novel hybrid-structured optical fibers and the devices based on them.

OCIS codes: (060.4005) Microstructured fibers; (320.7140) Ultrafast processes in fibers; (130.6010) Sensors.

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1. Introduction

Microstructured optical fibers (MOFs) have many applications in photonics. Various types of optical fiber devices and sensors have been fabricated by use of MOFs [1–9]. One of the attractive features of MOF is the selective infiltration, which allows different types of liquids fill into the selected air-holes, thus changing the guidance properties of the fiber. One of the commonly used methods of selective infiltration is to block the air holes that are not to be infiltrated and then fill those remain opened [10], such as collapsing air-holes [11,12], injection-cure-cleaving [3], splicing MOF with a single-hole hollow-core fiber [8, 13], lateral access to the air holes [14,15] and direct manual gluing [7,9,10]. The central air hole can be selectively infiltrated by collapsing other air-holes of the MOF with arc fusion [12], which only needs using a conventional fusion splicer, but the demand of selective infiltration of one or a few air-holes in the cladding region is hard to be fulfilled. Injection-cure-cleaving can infiltrate the central hollow core with differential filling speed that depends on the size of the air holes [3], and the usage of curable glue in combination with differential capillary forces makes it a general method of filling any group of air-holes with similar size. However, such a method may become invalid if the selected air-holes exhibit almost the same diameter as the holes that are not to be filled. Recently, J. Canning et al have demonstrated that materials can be selectively infiltrated into the air-holes by splicing a single-hole hollow-core fiber to the MOF [8,13]. The single-hole is aligned to the selected air-hole of the MOF and the other holes are blocked by the solid cladding of the single-hole fiber. Such a technique allows for multiple, accurate and selective filling of MOFs, however, a hollow fiber with a matched single-hole size is needed and only one hole can be filled after the fusion splice. The technique of lateral access to the air holes of the MOFs has also been developed and can be performed by blowing a hole through the fiber wall using a fusion splicer and air pressure [14] or by focused ion-beam milling [15], and the materials are subsequently infiltrated into the MOFs through the side-opened hole. Such a technique can be employed to selectively fill either some of the cladding holes or the hollow core of the MOFs however, an accurate filling may not be achieved due to the difficulty in opening only one or a few selected air-holes in the cladding region. A more versatile approach is the direct manual gluing, typically under a microscope. In this method, a glass tip of submicrometer scale is used to drop UV curable polymers into the air-hole before blocking it and hence a flexible and well controlled air-hole infiltration can be realized [9, 10]. However, different glass tips may need to be used for different air-hole sizes and when the diameter of the air-hole changes greatly in the cross-section of the MOF, substantial operation inconvenience is created.

In this paper, an efficient, precise, flexible and reliable method for selective infiltration of MOFs is demonstrated to overcome above mentioned difficulties, with the assistance of femtosecond (fs) laser micromachining. In this method, all the air-holes of the MOF are firstly blocked with a section of conventional single mode fiber (SMF), of which the length is about 10 µm. Then the air-holes selected to be filled are opened up by fs laser direct drilling through the blocked fiber end. Materials can be infiltrated into the selected air-holes from the micromachined fiber end by the well-known capillary action. With this method, any of the air-holes in the cross-section of the MOF can be precisely infiltrated, which opens up a new and efficient way of selective infiltration which has high potential in fabrication of novel hybrid-structured fibers and sensors.

2. Fabrication method

To demonstrate the selective infiltration method, a 20-cm length of LMA-10 fiber (NKT, Photonic Crystal) with an endlessly single-mode core was used in our experiment. The air-holes are hexagonal arranged with the hole-diameter of about 3.4 µm and the average hole-to-hole spacing of about 7.5µm. A schematic flowchart of our selective infiltration process is

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illustrated in Fig. 1, which includes three steps: (1) conventional fusion splicing and laser cleaving; (2) selective laser drilling and (3) infiltration. For the laser micromaching in the first two steps, fs laser pulses (λ = 800 nm) of 120-fs duration with repetition rate of 1 kHz were used. As depicted in Fig. 2, the pulses were focused onto the fiber samples by microscopic objectives. The pulse energy was continuously adjustable in the range between 0 and 1 mJ by rotating the half-wave plate incorporated with a polarizer, and hence the on-target pulse energy can be precisely controlled. A CCD camera was used to monitor the micromachining processes in real time. Fiber samples were mounted onto a computer controlled three-dimensional (3-D) translation stage, of which the positioning accuracy was 40 nm.

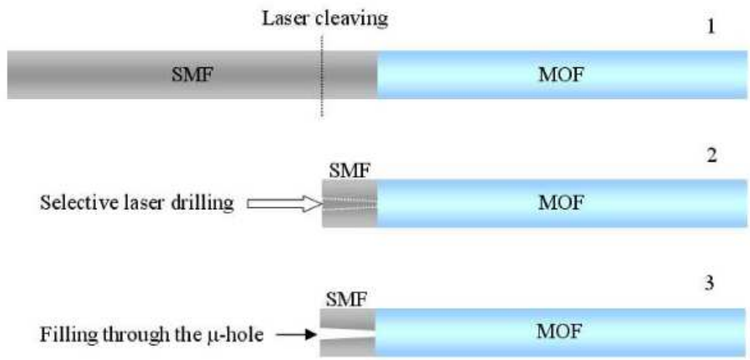

Fig. 1. (Color online) Flowchart of selective infiltration with the assistance of femtosecond laser micromachining. (1) Fusion splicing and laser cleaving; (2) laser drilling; (3) infiltration.

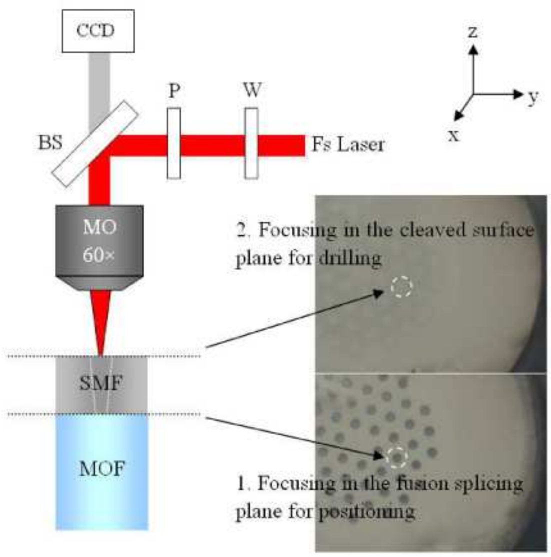

Fig. 2. (Color online) Experimental setup and laser focusing process illustration. CCD, charge-coupled device camera; W, half-wave plate; P, polarizer; BS, beam splitter; MO, microscopic objective. The insets in the right panel show the images of the cleaved sample formed in the fusion splicing plane and the cleaved surface plane, respectively.

The 20-cm-long LMA-10 photonic crystal fiber (PCF) was firstly spliced with a section of SMF (~10-cm in length) using a conventional fusion splicer. Then the spliced fiber sample was mounted onto the 3-D translation stage in parallel to the y-direction and was subsequently cleaved near the splicing point by the fs laser pulses focused by a 20 × objective lens with a numerical aperture (NA) of 0.50 and a working distance of 2 mm. During the

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laser-cleaving process, the on-target pulse energy was 5 μJ and the spliced fiber sample was translated in the x-direction, which was perpendicular to the fiber axis, with a speed of 100 μm/s. A micro-groove could be created by such a laser scanning process, at the position ~10 μm away from the splicing point on the fiber surface. The fiber sample was then cleaved by the local stress introduced by the micro-groove. The majority of the cleaved surface was rather smooth, as shown in the insets of Fig. 2. After the laser-cleaving process, the spliced end of the PCF was fully blocked by a section of ~10-μm-long SMF. The air-holes to be selectively filled were then opened up by direct fs laser drilling from the cleaved end of the fiber sample, as shown in step 2 of Fig. 1. To perform a selective drilling in the cleaved fiber end, an on-target pulse energy of 3 μJ and an objective lens with NA of 0.85 and a working distance of 300 μm were employed, as shown in Fig. 2. The laser cleaved fiber sample was mounted onto the 3-D translation stage again in parallel to the z-direction. The laser was firstly focused into the plane of fusion splicing to observe the target air hole and to move this hole to the laser focus in this plane. Then the fiber sample was moved downward for ~10 μm in parallel to the z-direction before drilling the hole from the cleaved surface. The images of the cleaved surface and the interface of the fusion splicing of the fiber sample are shown as insets in the right panel of Fig. 2. Finally, the drilled fiber end was immersed into the liquid to be infiltrated. Once the infiltration procedure was completed, the ~10-μm-long SMF introduced in the step 1 was cut off by conventional fiber cleaver.

The microscopic images of two selectively infiltrated LMA-10 fiber samples, which were filled with standard refractive index (RI) liquid with the RI value of 1.50 (from Cargille Laboratories), are shown in Fig. 3. The samples with only one air-hole infiltrated are referred to as A-hole and B-hole samples for short, respectively. One can see clearly from the images that the RI liquid has been injected into the selected air-hole and the neighbor holes are not affected, which implies that the fs laser-assisted selective infiltration method can be readily employed to create selectively infiltrated MOFs.

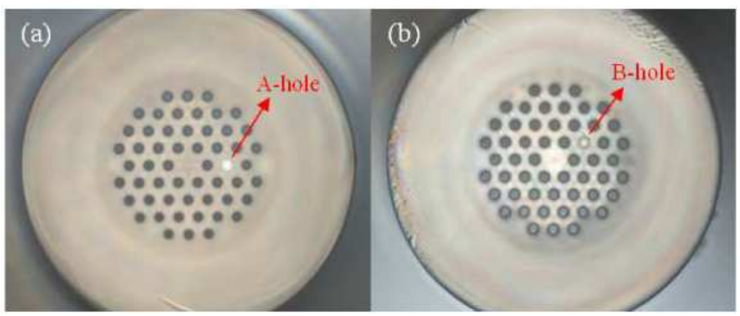

Fig. 3. (Color online) Microscopic images of selectively infiltrated samples. (a) A-hole infiltrated; (b) B-hole infiltrated.

It is worthy noting that, fs laser is not a must in this method, since ablation and drilling of fiber materials can also be performed by other types of lasers, such as UV lasers [16,17]. However, the surface quality of micromachining using fs laser would be better due to the smaller heat affecting zone associated with ultrashort pulse duration. Furthermore, precise infiltration of multiple materials can also be realized through the selective infiltration method simply by repeating the procedures shown in Fig. 1.

3. Result and discussion

To investigate the sensing properties of the selectively infiltrated fiber samples, we spliced both ends of the 5-cm-long samples with SMF fibers for A- and B-hole samples, respectively. A broadband light source and an optical spectrum analyzer (OSA) with a resolution of 0.01 nm were connected with the samples. A-hole sample has been firstly demonstrated by D. K. Wu et al, which exhibits ultrahigh RI sensitivity and detection limit [9].

#130315 - $15.00 USD Received 17 Jun 2010; revised 29 Jul 2010; accepted 30 Jul 2010; published 6 Aug 2010

In our experiment, A-hole sample was gradually warmed up from the room temperature to 50 °C, and was found to exhibit similar results to that reported in Ref [9]. Figure 4(a) presents the transmission spectra of A-hole sample at the temperature of 35 and 45 °C, respectively. The resonant wavelength shifts was ~100 nm corresponding to the temperature increment of 10 °C. For B-hole sample, a lossy band, of which the FWHM is about 60 nm, can be observed instead of the discrete resonant peaks in the case of A-hole sample, as shown in Fig. 4(b). This lossy band is possibly formed by the strong coupling of the fiber core mode and the infiltrated high-index rod modes. The B-hole sample is also ultrasensitive to the RI of the infiltrated liquid and the resonant wavelengths shifts was ~100 nm when the temperature was increased from 35 to 45 °C. The different resonant wavelengths corresponding to the A-hole and B-hole samples are possibly resulted from the difference of the air-hole diameters of the two samples, as the air-hole diameters are not critically identical during the fabrication and the resonant wavelengths are extremely sensitive to the hole-diameter besides the hole-index.

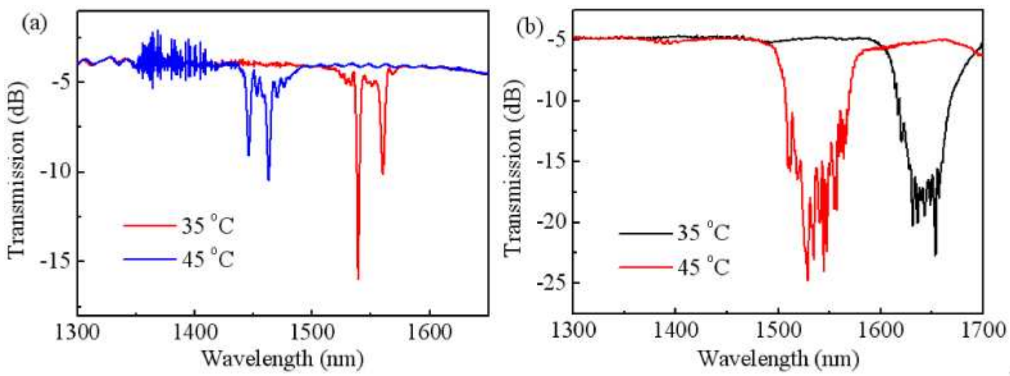

Fig. 4. (Color online) Transmission spectra of the MOF with (a) A-hole and (b) B-hole infiltrated by 1.50-RI liquids at different temperatures.

4. Conclusion

In conclusion, we have demonstrated an accurate, flexible and reliable method for selective infiltration of MOFs with the assistance of fs laser micromachining. Such a method can be employed for precise infiltration of any type of the air-hole in the cross-section of the MOF and can potentially be implemented into multiple material infiltration, which opens up a highly efficient selective infiltration approach for the fabrication of novel hybrid-structured fibers and the devices based on them.

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