Selective opening of airholes in photonic crystal fiber

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We introduce a femtosecond-laser-based technique for selective opening of airholes in photonic crystal fibers (PCFs). With this technique, selective filling and inflation of the airholes in the PCF cladding are demonstrated. The technique may find important applications in tailoring or altering PCF characteristics and make it possible to seamlessly integrate various components/functions into PCFs. © 2010 Optical Society of America

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The photonic crystal fiber (PCF) with a periodic array of airholes running along its length has attracted significant interest recently [1,2]. The precise arrangement of airholes and their index profiles throughout the cladding region allow various types of PCFs with novel properties to be designed. Endlessly single-mode operation, light-guidance in hollow air-core, and very high nonlinearity and birefringence are a few of the novel properties of PCFs that may not be achieved with conventional single-mode fibers (SMFs) [3,4]. Apart from the high level of flexibility in the PCF fabrication process, novel functionality may be added to PCFs by postprocessing [5–8]. Techniques for postprocessing PCFs include tapering and inscription of periodic structures that are widely adopted for conventional fibers and selective filling or pressurization of airholes, which is unique to PCFs. Examples of PCF postprocessing include selective filling of airholes with an index tunable polymer to realize birefringence tunability [5], inflating/deflating airholes to reduce splice loss and to achieve in-fiber mode conversion [6,7], and infiltrating submicrometer gold into a selected hole of a polarization maintaining PCF to achieve polarization- and wavelength-dependent transmission [8]. All these examples rely on the selective opening or closing of airholes within the cladding region. We previously demonstrated selective filling of PCFs by using a conventional fusion splicer [9], but it lacks the freedom to choose arbitrary airholes for filling. In this Letter, we report a technique for selective opening of airholes and demonstrate the selective filling and inflation of arbitrary holes in the PCF cladding.

Our approach starts by sealing all the airholes of a PCF by a thin layer of silica and then drilling individual holes through the layer by a femtosecond IR laser (fs-laser). With reference to Fig. 1(a), the PCF is first spliced to a conventional SMF by a fusion splicer. The SMF is then cleaved at a location about 30 μm from the splicing point. The splicing parameters are adjusted so that airhole deformation during splicing is minimized, while the splice is reasonably strong to survive the cleaving [10]. The thin layer of SMF seals all the airholes, but the end facet of the PCF beneath the thin silica layer can be clearly viewed under a microscope, allowing an individual airhole to be selected and located. Figure 1(b) shows the microscopic view of the end facet of a large-mode-area PCF [LMA-10, NKT Photonics A/S, scanning electron micrograph (SEM) photograph is shown in Fig. 2(a)] with an ~30 μm silica layer on top of it. The focal plane is then raised to the top of the SMF, and a Ti:sapphire fs-laser is used to drill microholes down to the end surface of the PCF, which opens a selected hole.

The fs-laser operates at a wavelength of 800 nm and emits light pulses with a duration of ~120 fs at a repetition rate of 1 kHz. The light pulses were focused onto the top facet of the thin SMF layer by a microscope objective (×20, NA = 0.5), and the focal spot diameter ($1/e^2$ of intensity) is estimated to be 2 μm. The pulse energy was adjusted so that a cone-shaped microhole is drilled throughout the SMF layer. Before drilling, we carried out experiments on a few SMF samples to investigate the coning depth and shape of the microholes. It was shown that pulses with an average energy of ~3 μJ resulted in microholes with a depth of ~35 μm and a diameter of ~3 μm at the PCF–SMF interface. With the help of the optical microscope, the target airholes to be opened can be accurately located and the silica layer on top of the holes can be removed by drilling with the fs-laser. Figures 1(c) and 1(d) show, respectively, the top and side views of the LMA-10 sample

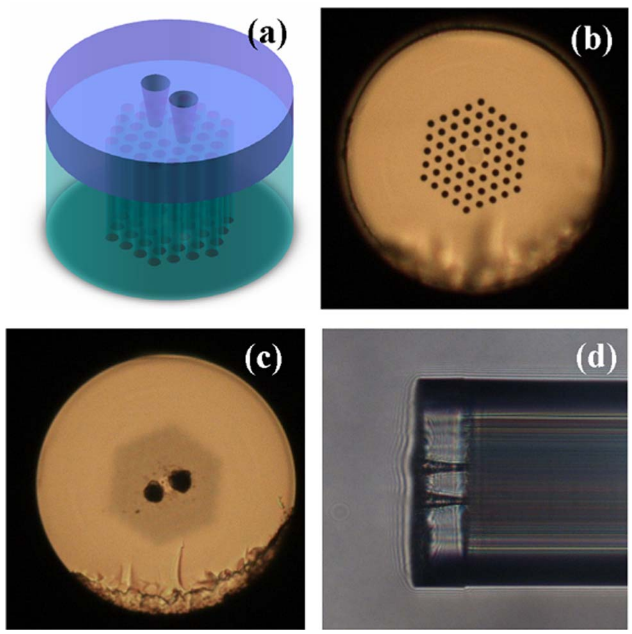

Fig. 1. (Color online) (a) Schematic showing selective opening of holes. Microscopic view of the fiber end (b) before drilling when the focal plane was tuned to the PCF/SMF interface and (c) after two holes were drilled and the focal plane was tuned to the top surface of the SMF. (d) Side view of the holes drilled. The thickness of the SMF section is ~30 μm.

with two holes adjacent to the core being opened. The diameters of the two holes at the PCF/SMF interface are measured to be ~3.5 μm, a little bit larger than the airhole diameter of the PCF (3.35 μm) but much smaller than the pitch between the adjacent airholes (7.4 μm). This ensures that the peripheral holes are intact but opens the target holes only. With the current experimental setup, we should be able to open any single hole in a PCF with a pitch larger than ~3.5 μm. By using a lens with a higher magnification and a larger NA, which corresponding to a smaller diffraction-limited spot size, it would be possible to open individual holes in a PCF with an even smaller pitch.

After the selected holes are opened from the fiber end, various postprocessing techniques, such as filling liquid or gas into the holes and inflating the holes, may be carried out. Figure 2(b) shows an example of LMA-10 [Fig. 2(a)] with two holes filled with UV-curable epoxy. To fill the holes, one end of the PCF was first prepared by the aforementioned technique to selectively open two holes [Fig. 1(c)], while the other end was cleaved and all airholes were left open. The end with the two opened holes was then inserted into a capillary filled with NOA89 liquid photopolymer, which was subsequently sucked into the opened holes by the capillary effect. The PCF with the coating removed was then cured by a UV lamp. The two opened holes were neatly filled with the polymer, and the rest remained intact. With this technique, we may selectively fill any holes with a gas, liquid, or metal.

Figures 2(c)–2(f) show examples of selected hole inflation through selective pressurization and a local heating/tapering process. In achieving selective hole inflation, one end of a PCF was first prepared by the selective hole-opening technique to open two [Figs. 2(c), 2(d), 2(g), and 2(h)] or six [Figs. 2(e) and 2(f)] holes, while the other end of the PCF is spliced to the SMF, sealing all the airholes. The fiber end with the opened holes was connected to a nitrogen gas cylinder through an airtight connector. The holes were then pressurized at a preset pressure and evenly heated with a traveling flame at the same time. Figure 2(c) shows the resulting cross section of the LMA-10 PCF that was heated while the two holes adjacent to the core were subjected to a pressure of 6 bars. Obviously, only the two holes connected to a high pressure were enlarged, while the others remain intact. Through this process, the cross section of LMA-10 PCF becomes nonsymmetrical and birefringence is introduced. Figure 2(e) shows another sample made from the same LMA-10 but with six holes opened and pressurized with a larger pressure of 7 bars. Comparing Fig. 2(c) with Fig. 2(e), it is evident that a higher pressure enlarges the holes to a larger degree.

Tapering the fiber when it is heated and pressurized leads to a much larger hole expansion in the taper waist, as shown in Figs. 2(d) and 2(f). During the tapering process, diameters of holes with a lower gas pressure are reduced (deflated) and a high diameter contrast between the holes with and without pressurizing are obtained. This could significantly modify the properties of the PCFs. For example, significant birefringence may be introduced to the samples shown in Fig. 2(d). Figure 2(h) shows the cross section of the taper waist made from a polarization maintaining PCF [PM-1550, NKT Photonics A/S; a SEM of the original PCF is given in Fig. 2(g)] when

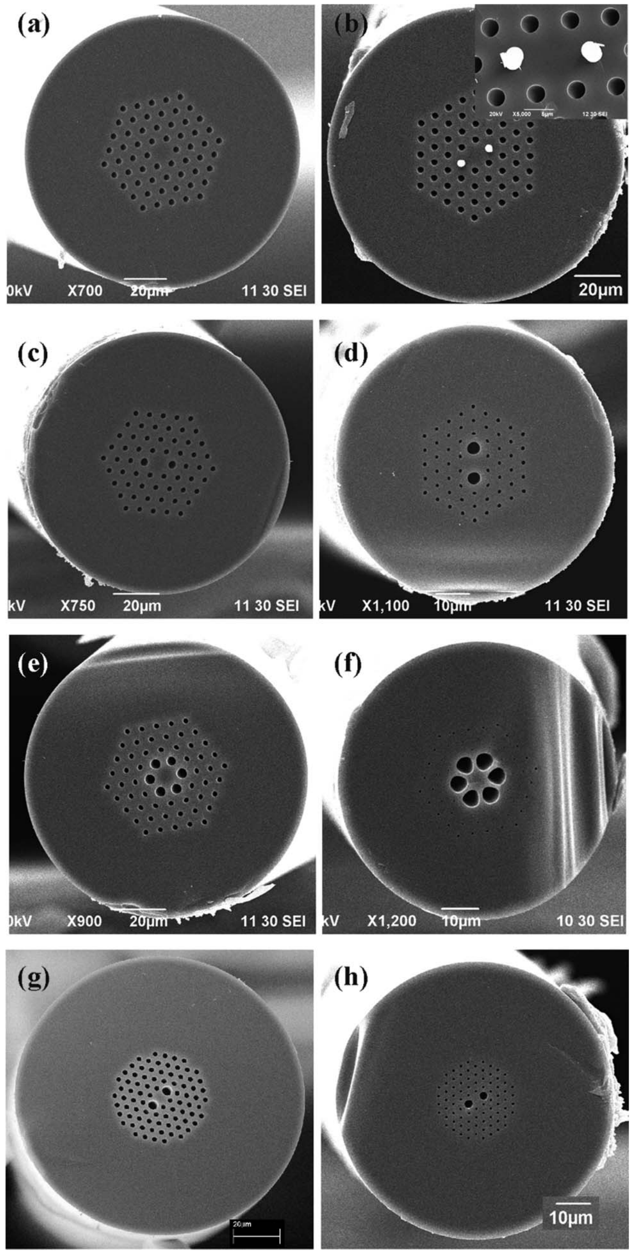

Fig. 2. SEM of fiber cross sections. (a) LMA-10. (b) LMA-10 with two holes filled with a photopolymer. LMA-10 with two holes pressurized (c) at 6 bars when heated and (d) at 7 bars and tapered. LMA-10 with six holes pressurized (e) at 6 bars when heated and (f) at 7 bars and tapered. (g) PM-1550 and (h) tapered PM-1550 with two bigger holes pressurized at 6 bars.

the two bigger holes were pressurized at 6 bars. The two bigger holes are still sufficiently larger even if the fiber is downtapered from the original 125 to 81.7 μm, while other holes are substantially reduced in size.

We measured the group birefringence of the tapered PCF by incorporating it into a Sagnac loop with both ends spliced to a standard SMF. The light propagating the birefringent section of the altered PCF generates interference fringes because of the propagation of nondegenerated fundamental modes. The wavelength spacing $\Delta\lambda$ of the interference fringes in wavelength domain is

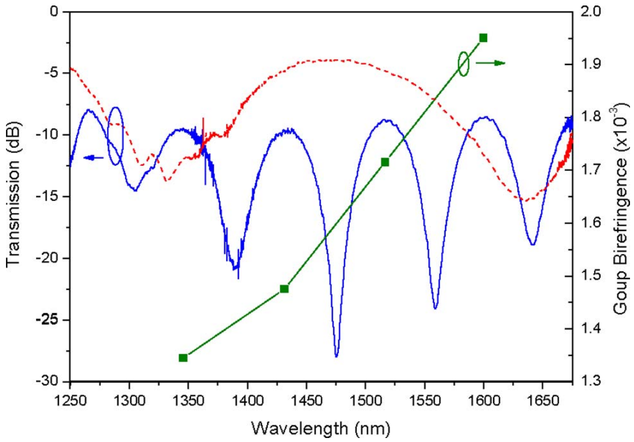

Fig. 3. (Color online) Interference fringes of the Sagnac loop interferometer for a tapered LMA-10 (dashed red curve) and PM-1550 (solid blue curve) and the measured group birefringence of the tapered PM-1550 (solid green curve) as a function of wavelength.

related to the fiber length L and its birefringence Δn by [11]

$$\Delta\lambda = \frac{\lambda^2}{\Delta n L}, \tag{1}$$

where λ is the geometric mean of the two adjacent dip wavelengths. The interference fringes of the tapered LMA-10 [Fig. 2(d)] and the tapered PM-1550 [Fig. 2(h)] are shown in Fig. 3. The results indicate that an average group birefringence of 3.6×10^{-4} at 1550 nm was obtained for a tapered LMA-10 PCF with two holes open. An even higher group birefringence of larger than 1.8×10^{-3} 1550 nm was obtained for the tapered PM-1550 with the two bigger holes pressurized. In both cases, the fiber was tapered to a length of 20 mm and pressurized at 6 bars. For comparison, the original LMA-10 fiber has negligible birefringence because of the hexagonal symmetrical structure, while the original PM-1550 has a birefringence of 7.8×10^{-4} at 1550 nm [11]. The insertion losses of both fiber tapers were measured to be lower than 0.2 dB at 1550 nm. The resulting high birefringence may find applications in all-fiber polarimetric sensing with a significantly reduced fiber length. Another advantage of the selected hole inflation and tapering is that splicing to other incompatible fiber can be avoided and all PCF components can be fabricated with very low losses.

In conclusion, a technique for selective opening of holes in PCFs is introduced. The technique is expected to play an important role in the postprocessing of PCFs for the purpose of developing novel PCF-based functional devices and sensors. With this technique, we have successfully demonstrated selective filling and inflation of holes of PCFs and achieved significantly enhanced birefringence by inflating two of the holes in commercial PCFs. The combination of the proposed selective hole-opening technique and other postprocessing techniques is expected to facilitate tailoring the characteristics of the PCFs and make it possible to seamlessly integrate special functional devices into PCFs with low insertion losses.

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