Fabrication of all-solid photonic bandgap fiber coupler

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We report the fabrication of a tunable all-solid photonic bandgap fiber coupler based on the side-polishing technique. This device is believed to be the first demonstration of a photonic bandgap fiber coupler to eliminate the contamination of the open air holes. By adjusting the length of the interaction section, the tunable coupling ratio as much as 92.5% at 1550 nm is achieved. The investigation of the spectrum properties shows that the coupler has excellent tunability properties, for which the coupling ratio can be smoothly and continuously controlled. © 2007 Optical Society of America

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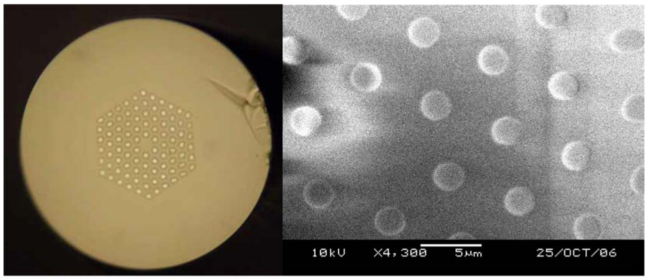
Microstructured optical fibers (MOFs) have attracted much attention due to their unique characteristics and controllable features. MOFs are generally classified in two classes: index-guiding MOFs, which guide light by total internal reflection with a high-index core and air-hole cladding, and photonic bandgap fibers (PBGFs), which confine the light in the fiber core (with a low index, such as air) due to the photonic bandgap (PBG) effect of fiber cladding. The all-solid PBGF is a new member of PBGFs in which the cladding comprises an arrangement of isolated high-index rods in a low-index background [1,2]. All-solid PBGFs provide a promising technology to fabricate bandgap materials with usual processes used in conventional fiber drawing. A MOF coupler that couples light from one MOF to another is a basic device for a MOF-based fiber-optic system. Several MOF couplers have been reported [3–5] in the literature in which the couplers are fabricated by use of the fused biconical tapered method or side-polishing technique. All these couplers investigated so far have been based on index-guiding MOFs. Although several theoretical investigations about PBGF couplers have been reported [6,7], to our knowledge no experimental investigation has yet been carried out for PBGF couplers.

In this Letter we report a tunable PBGF coupler fabricated by the side-polishing technique. Side-polishing techniques in fiber optics have been widely exploited to implement various tunable optical devices [8]. Conventionally the fiber is set into a substrate block on a large radius. The combined fiber and block are first ground and then polished to within a few micrometers to the fiber-core. For fiber-coupler fabrication, two side-polished fibers are mated with each other to bring the fiber cores into proximity, in order to achieve evanescent field coupling between the cores of the fibers. The coupling efficiency can be easily adjusted by controlling the length of the interaction section. Compared with the index-guiding MOF-based side-polished coupler, the coupler that uses the all-solid PBGF eliminates the contamination of the open air holes in the polished region, which is critical for decreasing the excess loss of the coupler. The all-solid PBGF coupler shows a tunable coupling ratio up to 92.5% at 1550 nm. The investigation of the spectrum properties shows that the coupling ratio can be smoothly and continuously tuned by controlling the interaction length.

The all-solid PBGF used in this Letter has been reported recently [9]. By introducing an index depressed layer around the high-index rod in the unit cell of photonic crystal cladding, the transmission loss as low as 2 dB/km within the first bandgap is realized. The attenuation at 1550 nm wavelength is $\sim$13 dB/km, which is adequately low for practical experiment. Figure 1 shows the optical micrograph and scanning electron micrograph (SEM) of the fiber cross section. The diameter of the fiber is 175 μm, and the lattice spacing Λ is $\sim$7.23 μm.

The silica block (also called half-block) with a dimension 30 mm$\times$8 mm$\times$6 mm was first cut to form a groove, with a 250 mm radius of curvature, 250 μm in width, 200 μm in depth. Then the all-solid PBGF was buried in the groove, as shown in Fig. 2(a). Epoxy (EP-TEK 353 ND A/B, Epoxy Technology, Inc.) was used to fix the PBGF in the groove. There are two steps in the polishing process: first the half-block was roughly polished on a cast iron plate with alumina powder of $\sim$1 μm size, and then it was finely



(a) (b)

Fig. 1. (Color online) (a) Optical micrograph of the fabricated photonic bandgap fiber. High-index and low-index regions appear lighter and darker, respectively, in the image. The outer diameter of the fiber is 175 μm. (b) SEM of the fiber cross section close to the core. Only the germanium doped parts can be identified within each periodical cell.

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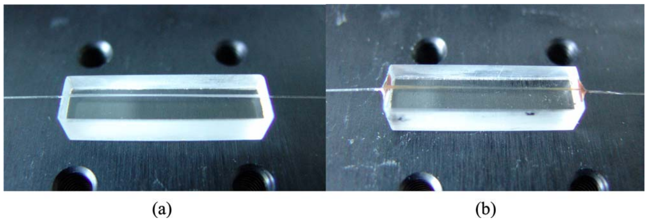

Fig. 2. (Color online) (a) Silica block with an all-solid PBGF buried in the groove. (b) Polished half-block in which the all-solid PBGF was embedded.

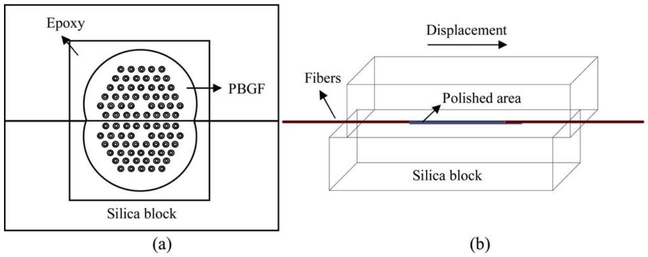

Fig. 4. (Color online) (a) Schematic of the mated side-polished half-blocks. (b) Schematic of the tunable mechanism. By longitudinally adjusting the relative positions of the upper half-block, the coupling ratio could be tuned smoothly and continuously.

polished on an expanded polyurethane plate with alumina powder of ~0.5 μm size. The ultrasonic cleaning was employed to get rid of the polishing powder at last stage. Figure 2(b) shows the polished half-block in which the all-solid PBGF was embedded. Figure 3 shows a schematic top view of the half-block and micrographs of the polished surface. The micrographs at the bottom show the left, middle, and right sections of the polished PBGF. The polished depth is a key factor to determining the coupling ratio. It could be roughly calculated by the length of the polished PBGF (~12.2 mm) and the curvature of the groove (250 mm); the polished depth is calculated as ~74.5 μm.

The PBGF coupler was assembled by mating two identical half-blocks with each other. An index-matching liquid with a refractive index equal to 1.46 was used to remove the air gap between the two side-polished half-blocks. After they were combined, alignment of two side-polished half-blocks was done using a miniature holder equipped with a micrometric screw. We can adjust the coupling efficiency by controlling the length of the interaction section, which is determined by the relative displacement of the half-blocks. A micrometer was used to push the upper half-block. Figure 4(a) shows the schematic of the mated side-polished half-blocks, and Fig. 4(b) illustrates the schematic of the tunable PBGF coupler. The tunability was realized by longitudinally offsetting the relative positions between two polished half-blocks.

The PBGF was spliced to standard single-mode fiber (SMF) by use of a modified routine on a commercial splicer. Due to mode mismatch between the SMF and the PBGF, the loss across the splice was ~2 dB at 1550 nm, which is repeatable and reliable in measurement. The coupling ratio is defined as the ratio of optical power at one output port (coupled port or through port) to the total power of the two output ports. First we achieve the maximum power coupling by longitudinally adjusting the relative positions between the mated half-blocks, and then we measure the optical powers at two output ports individually as a function of the longitudinal displacement at a wavelength of 1550 nm. Figure 5 shows the coupling ratios of through and coupled ports varied in terms of longitudinal displacement. The coupling ratio of the coupled port had a maximum of 92.5% and then decreased with increasing longitudinal displacement. The coupling would disappear at ~200 μm displacement, which is not shown in the figure. The coupling ratio is symmetric with respect to two input ports, since the coupler was assembled by mating two identical half-blocks (PBGFs), which were polished with the same curvature and length. However, due to the fabrication imperfections of half-blocks, the measured maximum coupling ratio is 90% when the light was launched into another input port. Excess loss is defined as the difference between the total power transmitted through both of the output ports of the coupler and the transmission power of a single, unpolished PBGF. The excess loss mainly depends on the polished depth; it also depends on the surface flatness of the polished half-block. For the perfect

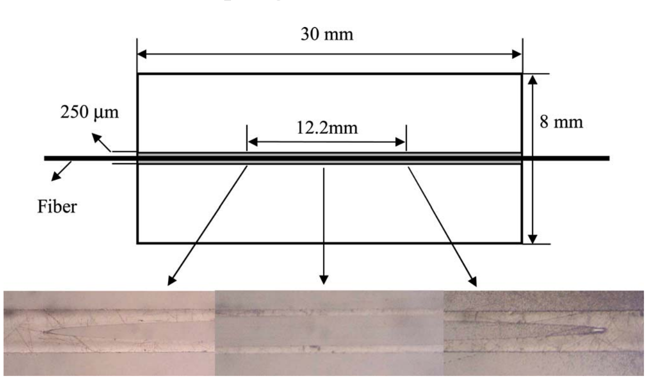

Fig. 3. (Color online) Schematic top view of the half-block and micrographs of the polished surface.

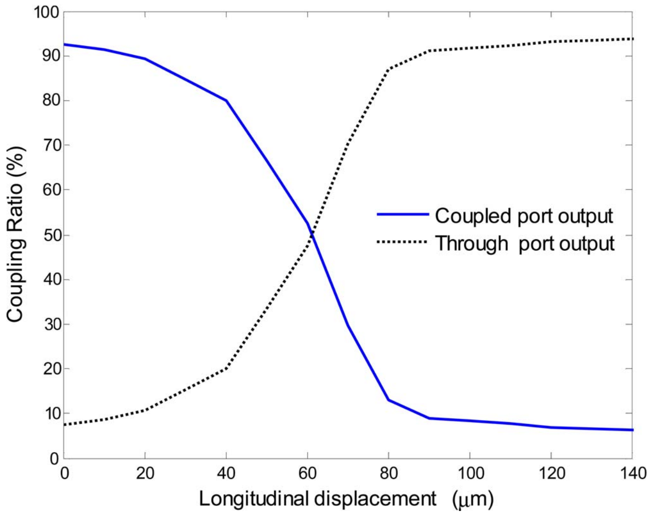

Fig. 5. (Color online) Coupling ratios of through and coupled ports as a function of longitudinal displacement at a wavelength of 1550 nm.

mating of two half-blocks, it is desirable to make the contact regions between two polished fibers flat. The role of the index-matching liquid is to improve the surface flatness of the half-blocks and to remove the small air gaps between them for better coupling efficiency. On the other hand, the use of the index-matching liquid avoids mechanical damage due to the sliding of the half-blocks. The excess loss might be due to two aspects: one is the scattering loss due to the unevenness of the surface of two polished fibers; the second is the radiation loss along the interface of two half-blocks, which could be considered as a defect of the whole fiber structure. We observed the excess loss is 1.5–2.5 dB for our PBGF coupler. The polished depth of ~74.5 μm is a result of the compromise between excess loss and coupling efficiency.

The spectra of the coupler have been measured with a broadband light source and an optical spectrum analyzer. Figure 6 shows the spectra of the coupled port with different longitudinal displacement. Compared with Fig. 5, we noticed that at displacement $d=0$ μm, the maximum coupling ratio is ~98.7% at 1570 nm, and more than 18 dB of channel isolation was observed. We can see that the spectrum shift to long wavelength and the coupling ratio can be smoothly and continuously tuned as the longitudinal displacement increases. The wavelength of the maximum coupling ratio as a function of the longitudinal displacement is shown as the inset of Fig. 6. The wavelength of the maximum coupling ratio could be shifted to short wavelength by increasing the polished depth, but the practical operation would be limited by the excess loss, which increases dramatically with the polished depth.

We believe that the coupling mechanism of our PBGF coupler is evanescent coupling. One of the characteristics of an all-solid PBGF is it has a set of high-index cladding states that are localized, or have a significant part of their weight, in the high-index rods. Since the PBG-guided core mode also has a portion of energy localized in high-index rods around the core [9], the cladding states in high-index rods would mediate interaction between the core modes through off-resonant coupling when the cores are sufficiently well separated [6]. Lægsgaard [6] has predicted that for a twin-core PBGF, the coupling length would exhibit maximum close to the short-wavelength cutoff of the transmission window. This characteristic is of interest for fabricating broadband tunable couplers. However, we noticed that 3 dB bandwidth is ~150 nm for our PBGF coupler. We believe the reason behind this observation is that the PBGF used in this Letter has a wide transmission window from 880 to 1600 nm [9]; at the red edge of the transmission window (around 1550 nm), the guide mode profile expands monotonically with wavelength. We believe that the location of the transmission window, mode area, coupling, and propagation losses over the transmission window of the PBGF are important parameters to be considered for broadband coupling.

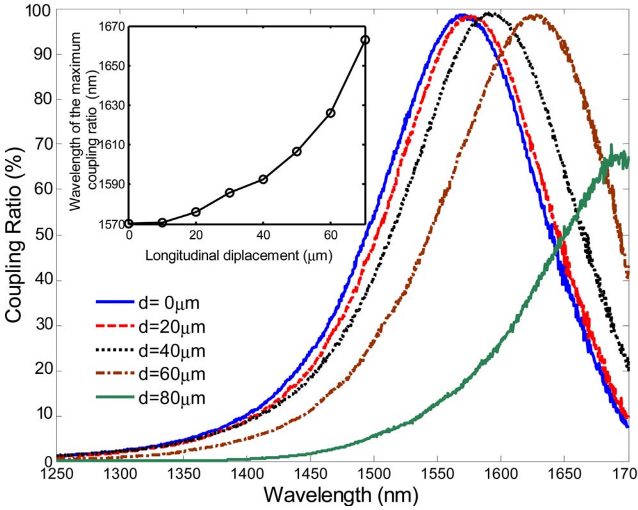

Fig. 6. (Color online) Normalized spectra of the coupling ratio for coupled port measured at longitudinal displacement $d=0$, 20, 40, 60, and 80 μm. The inset shows the variation of the maximum coupling ratio wavelength in terms of the longitudinal displacement.

In conclusion, we have fabricated what we believe to be the first tunable all-solid PBGF coupler based on the side-polishing technique. The evanescent field coupling between two PBGFs has been demonstrated by removing part of two PBGFs and mating them together. The tunability was realized by longitudinally adjusting the relative position between the mated half-blocks. It is shown that the coupling ratio can be smoothly and continuously tuned by controlling the interaction length. The coupling ratio up to 92.5% is achieved at 1550 nm; the spectrum measurement of the PBGF coupler shows that the maximum coupling ratio is ~98.7%, and the wavelength of the maximum coupling ratio increases with the longitudinal displacement.

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