Wavelength-division-multiplexing fiber coupler based on bending-insensitive holey optical fiber

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A wavelength-division-multiplexing (WDM) coupler has been made with a bending-insensitive holey optical fiber (HOF) by using the fused biconical tapered (FBT) method. The transmission band of the proposed HOF WDM coupler could be easily tuned by adjusting the pulling length during the FBT process. Interestingly, it was observed that the air-hole structure of the HOF should be maintained to have the property of a WDM coupler. As the air holes collapse, the HOF WDM exhibits high-pass-filter-like properties. The cross-sectional scanning electron microscope images of the implemented HOF WDM coupler are presented along with the light intensity distribution measured at the coupling region of the coupler. The proposed HOF couplers may also find applications in optical coarse WDM systems and optical fiber sensors. © 2010 Optical Society of America

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As the demand for large transmission capacity increases, the so-called fiber-to-the-home (FTTH) technology has attracted more attention [1]. Optical fibers for FTTH are asked to have low bending loss, because they are likely to be curved in a small curvature [2]. Photonic crystal fibers (PCFs) and holey optical fibers (HOFs) have been studied [3,4], especially the HOF that has one layer of air holes around a Ge-doped core, to achieve small bending sensitivity [2,5]. However, to be used in an HOF optical system, some basic fiber components for the HOF system itself should also be available. One of those components is a fiber coupler. Although a single-mode coupler based on PCF or HOF has been reported [6,7], those works focused on just having an ultrawide spectral bandwidth. In this Letter, we report a 2 × 2 HOF coupler that shows a sinusoidal transmission spectrum suitable for wavelength-division-multiplexing (WDM) applications. The coupler is fabricated by using the fused biconical tapered (FBT) method but with a ceramic heater, which is known to have better control than the conventional hydrogen flame heater [7,8]. The fabrication processes and the characteristics of the HOF WDM coupler are presented and discussed. The performance of the HOF WDM is demonstrated, and the high-pass characteristic of an over-elongated coupler is also presented.

The HOFs used for the experiments had one layer of air holes around a Ge-doped core within a 125 μm cladding, which could withstand a bending radius of up to 6 mm. During the process, the optical powers at both output ports of the coupler were monitored with a DFB laser (1550 nm) and two optical power meters. Figure 1 shows the pull signatures of the fiber couplers fabricated with HOF (upper red curve) and with conventional single-mode fiber (SMF) for reference (lower blue curve). To prevent air-hole collapse in the HOF, the ceramic heater temperature was intentionally made about 200°C lower than that of the conventional SMF coupler [6]. The same condition, including the temperature, was kept for the SMF coupler fabrication. In the experiment, it was observed that the coupling action commenced at elongation lengths of about 7 mm for the SMF case and 9 mm for the HOF case. As the elongation length increased, the coupling efficiency reached its maximum and then decreased. With further elongation, the so-called over-coupled regime [9], the coupling ratio oscillated with increasing frequency.

The side view of the HOF coupler implemented with a 21 mm elongation length was taken by an optical microscope. Figure 2(a) shows that the fiber diameter was reduced adiabatically from down to up. Figure 2(b) is the cross-sectional scanning electron microscope (SEM) image taken at near the very center of the coupler, indicated by the top arrow of Fig. 2(a), and its bird’s eye view is in Fig. 2(d). The cladding diameter was measured as reduced down to 7.6 μm, and the hole sizes became about

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Fig. 1. (Color online) Pull signatures of the fiber couplers fabricated with HOF (upper red curve) and with conventional SMF (lower blue curve).
0.6 μm. Figure 2(c) is the same image but taken a little apart from the very center, as indicated by the bottom arrow. We can see that each fiber maintained its original air-hole structure pretty well, with very small air-hole collapse. Figure 2(e) is the light intensity distribution taken at the fused area of the HOF coupler, after being cleaved, with a Micron viewer (Electrophysics 7290 A) at 1550 nm. Even with the severe fiber diameter reduction, the light field was well confined within the cores of both HOFs, but not a small amount of light field extended out of the cores, also. The same measurement was made with a visible light (633 nm). Compared to the mode field at a visible light, the field confinement of IR light was tighter [10].

With two overcoupled HOF couplers of elongation lengths of 21 and 23 mm, as shown in Fig. 3, the transmission spectra were measured. Especially with the 23 mm elongation, the coupler shows a well-developed sinusoidal coupling ratio with respect to wavelength. We can see several ripples, which might be caused by the interference among the cladding modes at the coupling region. We have also measured about 2 dB excess loss and 15 dB isolation.

For comparison, we investigated the HOF couplers fabricated with extra long elongation lengths. Figure 4 shows a series of transmission spectra of an HOF coupler, taken as the elongation length was increased from 33.1 to 34.3 mm. The inset is the SEM image of the cross section of the fused area.

The structure of the HOF having a Ge-doped core is similar to that of double-clad fiber. The silica region between the Ge-doped core and the air holes acts as an inner cladding. Of course, the region of air holes is working as the outer cladding. As the elongation increases, at first, the core mode extends out of the core but is still confined by the outer cladding. Therefore, the coupling of the HOF coupler starts later than that of the SMF coupler. However, with further elongation, due to too much reduced core size and the partial collapse of air holes, even the confinement by the outer cladding becomes weak. Figure 2 shows that the air-hole filling factor of Fig. 2(b) is smaller than that of Fig. 2(c), which confirms that air-hole collapse occurs because of the elongation process.

With this filling-factor reduction induced by elongation, the oscillating power-exchange behaviors of Fig. 1 might be understood at least qualitatively. In Fig. 1, considering only slowly varying oscillation, the HOF coupler shows more rapid oscillation than the SMF coupler. Because of the partial air-hole collapse in the HOF coupler, at the same elongation length, the distance between the fibers decreases, which is thought to give a larger coupling coefficient and results in the more rapid oscillation. The moderate oscillation peaks at the elongation of 20–22 mm of the HOF coupler might result from the interaction with the inner cladding layer. Finally, the noiselike fine peaks in both couplers might be from the interaction with the cladding–air interface. Because of the low fabricating temperature, the degree of fusion [12] was very small, so that we had a slightly fused coupler; two fibers were barely touched, as shown with Fig. 2. In the slightly
fused coupler scheme, the cladding–air interface of each fiber could support multimodes, and mode coupling among them could happen. Further, the large polarization dependency of the slightly fused scheme can be a cause of the complexity [12]. The polarization-dependent loss of the HOF coupler was 1.3 dB at 1310 nm and 2.4 dB at 1550 nm. However, further intensive and systematic investigation is necessary to have full understanding of the HOF coupler.

We also examined the transmission performance of the proposed HOF WDM coupler. Two 10 Gbps optical pulse trains were generated at wavelengths of 1310 and 1550 nm. After being transmitted 20 km SMF, the two pulse trains were launched together into the HOF WDM coupler and received at two output ports with different bands. At the HOF between the coupler and each receiver, bending was applied by winding the HOF three times around a cylinder of 6 mm radius, which gave 0.15 dB bending loss at 1310 nm. It increased up to 1.3 dB with 4 mm bending radius. For comparison, the same experiment was performed with a conventional SMF WDM coupler. Figure 5 shows the bit error rate (BER) performance of both couplers measured at the 1550 nm output channel. We can see that, for the SMF case, the BER was very low without bending but became very high with bending, up to a 13 dB power penalty. However, for the HOF case, there was no appreciable degradation with bending. At the 1310 nm channel, no appreciable power penalty was observed, either. Even though the fabrication process for the HOF couplers is not yet fully established, we can expect practical applications in the fields of fiber sensor systems [9] and coarse WDM networks [13].

It has been presented that a 2 × 2 WDM coupler was successfully fabricated with bending-insensitive HOF by using the FBT method and a ceramic heater. The coupling action of the HOF coupler commenced at a little longer elongation length than a conventional SMF coupler. As the elongation length increased, the optical power was coupled back and forth between two output channels; however, the HOF coupler showed more rapid coupling ratio oscillation than the SMF coupler. At this regime, the transmission was also oscillating with the input wavelength, and the oscillating frequency increased with the elongation length, which might be used for WDM applications. As the elongation was applied further to the HOF coupler, the air-hole filling factor decreased severely, and the coupler no longer showed WDM properties, but became a high-pass filter. The HOF coupler is expected to find applications in the field of smart sensor systems, also.

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