BRIEF PAPER

Fabrication of Polarization-Maintaining Photonic Crystal Fiber Coupler with Air Hole State Control Using CO_2 Laser Irradiation Technique

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SUMMARY Polarization-maintaining photonic crystal fiber couplers (PM-PCFCs) were fabricated using a CO_2 laser irradiation technique. We could control the states of air holes in the tapered region of couplers by adjusting the laser power density in the fusion and the elongation processes. It was demonstrated that the air hole remaining PM-PCFC exhibited polarization-splitting characteristics and that the air hole collapsed PM-PCFC had polarization insensitive coupling characteristics.
key words: *photonic crystal fiber, polarization-maintaining fiber, optical fiber coupler, polarization dependent coupling characteristics, CO_2 laser irradiation technique*

1. Introduction

Photonic crystal fibers (PCFs) that have air holes around the centers of their cross sections exhibit various interesting features not seen in conventional optical fibers by designing the sizes and the arrangements of the air holes. Examples of the features are endlessly single-mode, arbitral dispersion controllability, extremely high/low nonlinearity, high birefringence, and so on. At first, PCFs have been applied to functional fibers in optical fiber systems because of their unique features [1]. Recently, applications of PCFs as transmission lines have been investigated since low loss PCFs had been developed [2]. An ultra-wideband WDM transmission was reported using the feature of endlessly single-mode [3]. An ultra-high bit rate transmission using optimally dispersion controlled single polarization PCF was also proposed [4].

A polarization-maintaining PCF (PM-PCF) that is realized by an air hole arrangement in two-fold rotational symmetrically can exhibit higher modal birefringence compared to conventional polarization-maintaining fibers such as a PANDA fiber, an elliptical jacket fiber, and a bow-tie fiber [5]. Because of its high birefringence, PM-PCFs are expected to be the applications for optical transmission systems and optical sensing systems with polarization control. To construct PM-PCF transmission and sensing systems using PM-PCF features, optical fiber devices fabricated with PM-PCFs are preferred. An optical fiber coupler is one of the basic components in optical fiber systems; therefore a realization of PM-PCF coupler (PM-PCFC) is desired to construct PM-PCF systems.

In this paper, we report fabrications of PM-PCFCs using the CO_2 laser irradiation technique. The state of air holes in the PM-PCFC taper can be controlled by appropriate adjustment of laser power density in the fusion and the elongation processes. Coupling characteristics depending on the state of air holes in the coupler taper are experimentally clarified.

2. PM-PCFC Fabrications with Air Hole State Control

In fabrications of PCF couplers (PCFCs) including PM-PCFCs, states of air holes in the PCFC tapers should be controlled because the states of air holes in the PCFC tapers affect light propagations in the tapers i.e. the characteristics of the PCFCs depend on the states of air holes. Although fused optical fiber couplers are fabricated using gas burners or electric heaters in general, we used CO_2 laser irradiation technique for PM-PCFC fabrication. Since this technique can precisely control the energy to heat fiber, an accurate control of fiber temperature is possible in coupler fabrication. Therefore, it is suitable for PM-PCFC fabrications with air hole state control. It was reported that the state of air holes could be controlled in the elongation process of the PCFC fabrication using CO_2 laser irradiation technique in which the laser power density was appropriately adjusted as the PCFs were elongated and that wavelength characteristics of PCFCs depended on the states of air holes [6]. The technique also has advantages that are contamination-free and short fabrication time.

Figure 1 shows a PM-PCFC fabrication setup using CO_2 laser irradiation. The laser beam was irradiated to the sides of PM-PCFs through two cylindrical lenses. Using these lenses, the laser beam was focused in radial direction to fibers and defocused in longitudinal direction to fibers. The PM-PCFs were fixed to the mechanical stages with stepping motors. Tension members were used to apply tension to fibers stably, and also have a function to rotate fibers in the setting; therefore we can easily set the polarization axes of PM-PCFs parallel in the fiber setting to suppress polarization crosstalk in coupler outputs. The polarization axes of the PM-PCFs were set parallel, observing facets of twist

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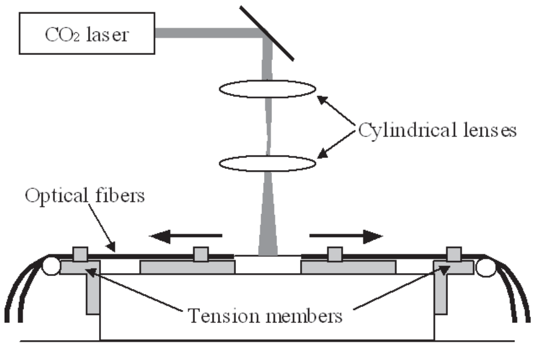


Fig. 1 PM-PCFC fabrication setup using CO_2 laser irradiation.

free PM-PCFs using a microscope. In the elongation process, the power density of the irradiated laser was appropriately increased to make fiber temperature constant because the temperature of laser irradiated fiber is decided by the irradiated laser power density and the fiber diameter. By the laser power density adjustment, the fiber break can be avoided, and the state of air holes in the tapered region can be controlled whether air holes were remaining or collapsed.

3. Experimental Results and Discussions

The cross section of the PM-PCF used for coupler fabrication is shown in Fig. 2. It has 6 air hole rings. The cladding diameter is 123.2 μm, and the air hole pitch is 4.3 – 5.5 μm. The diameters of large and small air holes are 4.9 μm and 2.7 – 3.4 μm, respectively. In the cross section, we defined the x-axis as the direction to major axis of the elliptical area surrounded by large air holes. The y-axis was defined as the orthogonal direction to the x-axis.

We used a pulsed CO_2 laser with 14.285 kHz repetition frequency for PM-PCFC fabrication. The maximum value of the averaged laser output power was 25 W. The diameter of the irradiated laser beam on fibers through two cylindrical lenses was ~ 14 mm in longitudinal direction to fibers. The increment of the laser power density was brought by the increment of the average laser power output and by decreasing the diameter of the laser beam in radial direction to fibers. Figure 3 shows the irradiated laser power density for time in the PM-PCFC fabrications. The CO_2 laser beam was irradiated for 100 seconds to fuse PM-PCFs before elongation. After fiber fusion, the PM-PCFs were elongated for 300 seconds with 60 μm/s elongation speed while CO_2 laser beam was irradiated to the PM-PCFs. In fabrication of PM-PCFC with air hole collapsed taper, the gradient of increment in temporal laser power density was made steeper compared to the air hole remaining PM-PCFC fabrication, so that the fiber temperature was made higher to obtain lower glass viscosity for air hole collapsing in elongation process.

Figure 4 shows photographs of the fabricated air hole remaining PM-PCFC taper side view. It is found that the air holes are remaining in the whole of the tapered region. The fiber diameter of the taper waist is ~ 38% of the fiber diameter before elongation. The taper length that is defined as the

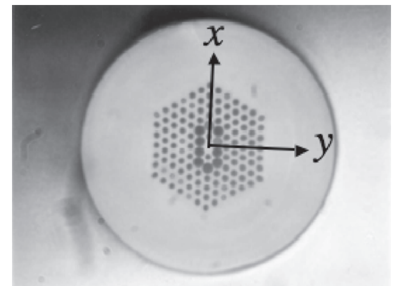


Fig. 2 Cross section of the PM-PCF for coupler fabrication.

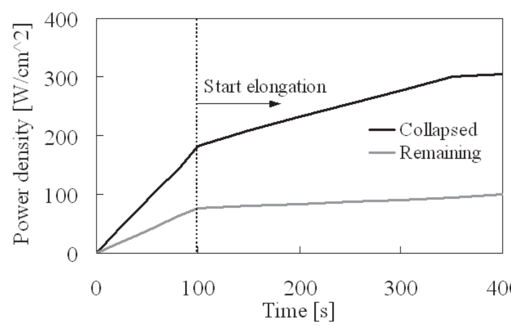
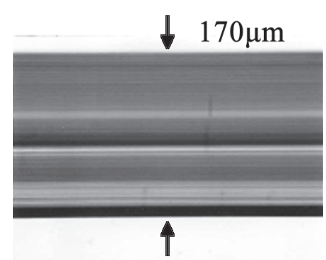
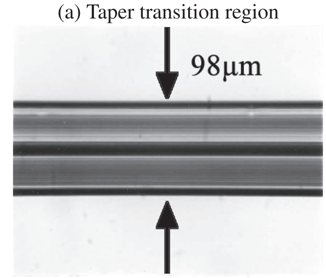


Fig. 3 Irradiated laser power density in PM-PCFC fabrications.



(a) Taper transition region



(b) Taper waist

Fig. 4 Photographs of fabricated air hole remaining PM-PCFC taper side view.

distance between the points of 10% diameter reduction was ~ 25 mm. Figure 5 shows a photograph of the fabricated air hole remaining PM-PCFC cross section at taper waist. It is found that the air holes are remaining and the polarization axes are almost set parallel. Figure 6 shows photographs of the fabricated air hole collapsed PM-PCFC taper side view. The air holes are collapsed at the taper transition region. The fiber diameter of the taper waist is ~ 14% of the fiber diameter before elongation. The taper length was ~ 22 mm, and

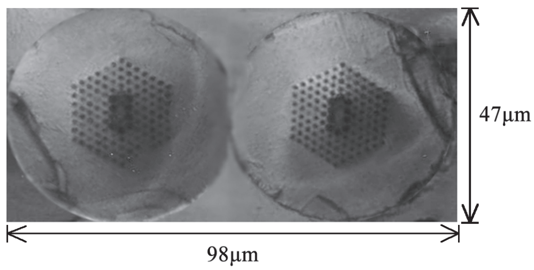
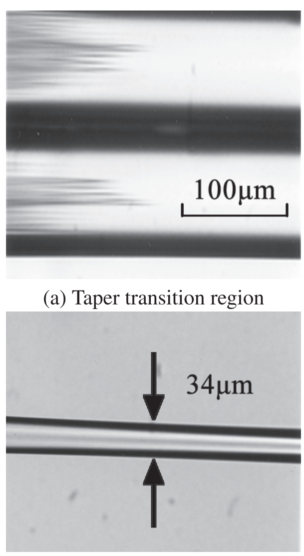


Fig. 5 Photograph of fabricated air hole remaining PM-PCFC cross section at taper waist.



(a) Taper transition region

(b) Taper waist

Fig. 6 Photographs of fabricated air hole collapsed PM-PCFC taper side view.

Table 1 Extinction ratios in fabricated PM-PCFCs.

Air holes	Polarization	Straight	Cross
Remaining	x	83%	17%
	y	19%	81%
Collapsed	x, y	54%	46%

the length of the air hole collapsed region was ~ 24 mm. As shown in these results, we could successfully control the state of air holes in the tapered region of the PM-PCFCs by adjustment of laser power density.

Coupling characteristics of fabricated PM-PCFCs at 1550 nm-wavelength were measured. They are summarized in Table 1. In the air hole remaining PM-PCFC, the extinction ratios at straight and cross ports for x-polarization were 83% and 17%, respectively. On the other hand, those for y-polarization were 19% and 81%. The polarization crosstalk at each port was up to −30 dB. It is found that the air hole remaining PM-PCFC exhibited polarization-splitting characteristics. It is considered that the characteristics were brought by the birefringence in the tapered region with air holes. Although the obtained characteristics are not sufficient in practical use, the improvement of the characteristics is expected by optimizing the shape of coupler taper such as a minimum taper diameter and a taper length. In the air hole collapsed PM-PCFC, the coupling characteristics were polarization insensitive, where the polarizations of the transmitted lights at the output ports were maintained. The extinction ratios at straight and cross ports were 54% and 46% for both x- and y-polarizations. The polarization crosstalk at each port was ~ −30 dB. It is considered that the characteristics were caused by the air hole collapsed PM-PCFC taper without birefringence.

The excess losses of fabricated PM-PCFCs were ~ 6 dB. This value is too high to use them in practical systems. It is considered that the loss is induced by the cutoff of fundamental mode in PCF taper [7]. We expect that optimally designing of the air hole arrangement and the taper profile is effective for the excess loss reduction.

4. Conclusions

In this paper, we reported the fabrications of PM-PCFCs using CO_2 laser irradiation technique. The states of air holes in PM-PCFC tapers could be successfully controlled by appropriately adjusting the laser power density. The fabricated air hole remaining PM-PCFC exhibited polarization-splitting characteristics. On the other hand, the air hole collapsed PM-PCFC had polarization insensitive coupling characteristics, where the polarizations of the transmitted lights at the output ports were maintained.

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