Coupling Characteristic Adjustment of Photonic Crystal Fiber Coupler with Length Control of Air hole Collapsed Region

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(Received 25th August, 2017; Revised 27th September 2017; Accepted 29th September, 2017; Published: 30th September, 2017)

Abstract- Coupling characteristics of a fused photonic crystal fiber (PCF) coupler are affected by a state of air holes in the coupler taper. The length of the air hole collapsed region in the air hole collapsed PCF coupler taper should be controlled to obtain desired coupling characteristics. However, it is difficult to control the length of air hole collapsed region for coupling characteristic adjustment in the elongation process of fused PCF coupler fabrication. In this paper, we proposed a new method for coupling characteristic adjustment in an air hole collapsed PCF coupler in which a length of air hole collapsed region is controlled. The air holes were collapsed at the end of elongation process in fused PCF coupler fabrication using CO\(_2\) laser irradiation. At first, the temporal variation of irradiated CO\(_2\) laser power density and the fiber elongation speed were set to fabricate a PCF coupler with ~18mm tapered region, where air holes in the coupler taper were not collapsed. To collapse air holes in the coupler taper, the irradiated laser power density was rapidly increased at the end of elongation process in coupler fabrication. The length of the air hole collapsed region was decided by the laser irradiation time after laser power density increment. It was demonstrated that the proposed method was effective for coupling characteristic adjustment in the PCF coupler with air hole collapsed taper, where the extinction ratio at cross port was successfully adjusted from 33% to 57% by increasing the length of the air hole collapsed region at coupler taper from ~6mm to ~12mm.

Key Words: Photonic Crystal Fiber, Fused Fiber Coupler, CO\(_2\) Laser Irradiation Technique

1. INTRODUCTION

Since a photonic crystal fiber (PCF) has unique features that are not observed in conventional optical fibers [1], PCFs are expected as functional fibers such as for a dispersion compensation [2,3], a supercontinuum generation [4,5], a wavelength conversion [6,7], and so on. PCFs are also expected as transmission lines for fiber optic communication systems with large transmission capacity using PCF features such as an endlessly single-mode, a flexible dispersion controllability, and a high birefringence for single polarization transmissions [8,9].

A PCF coupler [10-14] is one of the promising optical devices to construct systems using PCFs. In a PCF coupler fabrication, PCFs are fused and elongated, hence, the state of air holes depends on the condition of coupler fabrication. Since the state of air holes affects the light propagation in the PCF coupler taper, coupling characteristics of the PCF coupler depend on the state of air holes. It was reported that the wavelength characteristics of PCF coupler depend on whether air holes in the tapered region were remaining or collapsed, where the air hole remaining PCF coupler had gentle wavelength characteristics in extinction ratios at output ports compared with the air hole collapsed PCF coupler [12]. It was also reported that the polarization maintaining PCF coupler (PM-PCF coupler) with air hole remaining taper had polarization dependent coupling characteristics, and that the air hole collapsed PM-PCF coupler exhibited polarization independent coupling characteristics [14].

The extinction ratios at output ports of the PCF coupler with air hole collapsed taper are affected by the length of the air hole collapsed region in coupler taper. Therefore, the length of the air hole collapsed region should be controlled to obtain desired extinction ratios. However, precisely controlling the length of the air hole collapsed region is not easy by the previously reported coupler fabrication methods using CO\(_2\) laser irradiation [12,14].

In this paper, we propose a new method to control the length of the air hole collapsed region for coupling characteristic adjustment, in which the irradiated laser power density is rapidly increased at the end of elongation process in coupler fabrication and the length of air hole collapsed region is decided by the laser irradiation time after laser power density increment. It is demonstrated that the extinction ratios at output ports are successfully adjusted by the length control of air hole collapsed region using the proposed coupler fabrication method.

2. PHOTONIC CRYSTAL FIBER COUPLER WITH AIR HOLE COLLAPSED TAPER

A schematic model of a fused PCF coupler with air hole collapsed taper is shown in Fig. 1. The shaded region indicates that the air holes are collapsed. \(c_0\) is the major diameter of coupler taper before elongation. \(c_{\text{min}}\) is the minimum major diameter of coupler taper. In this paper, the taper length \(L_t\) is defined as a distance between the points of 10% diameter reduction. \(L_{\text{col}}\) is the length of air hole collapsed region. A light is launched into port 1 of the PCF coupler. The extinction ratios at straight and cross ports are defined as 100 \times \frac{P_3}{P_0 + P_3} [%] and 100 \times \frac{P_4}{P_3 + P_4} [%], respectively, where \(P_3\) and \(P_4\) are the output powers at ports 3 and 4. The
excess loss of the PCF coupler is given as 

\[ -10 \log ([P_1 + P_2]/P_1) \text{[dB]} \]

where \( P_1 \) is the input power at port 1.

Coupling characteristics of a conventional fused fiber coupler depend on the shape of tapered region, the taper length \( L_c \), and the elongation ratio \( \tau = \frac{c_{\text{out}}}{c_0} \). However, in a PCF coupler, the state of air holes in coupler taper also affects coupling characteristics due to the existence of air holes. It had been reported that the wavelength characteristics and the polarization dependence of extinction ratios were affected by the state of air holes; whether air holes in coupler taper were remaining or collapsed [12,14]. It had been also reported that the extinction ratios of the air hole collapsed PCF coupler depended on \( L_{\text{col}} \) in the tapered region of the coupler [12].

Hence, \( L_{\text{col}} \) should be controlled to obtain desired extinction ratios. In our previous studies on PCF coupler fabrications using CO\(_2\) laser irradiation, we had demonstrated that the air holes could be collapsed by laser power density adjustment in the elongation process of PCF coupler fabrication, where the laser power density was step-like increased [12] or the gradient of laser power density increment was made larger compared with that for air hole remaining PCF coupler fabrication [14]. \( L_{\text{col}} \) could be controlled by the time adjustment of step-like laser power density increment from the start of elongation or by adjusting the gradient of the laser power density increment. However, it is difficult to adjust the time or the gradient precisely to control the length of air hole collapsed region. For the problem, our group proposed a method to control the length of air hole collapsed region, where the air holes were collapsed using CO\(_2\) laser irradiation after elongation process of coupler fabrication, i.e. the air hole collapsing was isolated from the elongation process [13]. The length of air hole collapsed region could be easily controlled for extinction ratio adjustment. However, this method often caused taper deformations that are an origin of excess loss in coupler.

In this paper, we propose a new method to control \( L_{\text{col}} \) in air hole collapsed PCF coupler fabrication, where the irradiated laser power density is rapidly increased at the end of elongation process. The length of air hole collapsed region is decided by the laser irradiation time after laser power density increment. In this method, we first set the conditions to fabricate PCF coupler with air hole remaining tapered region, where a temporary variation of laser power density and an elongation speed are set. To fabricate PCF coupler with air hole collapsed taper, the laser power density is rapidly increased at the end of elongation process, where the power density for air hole collapsing is made much larger than that for fiber elongation. The desired \( L_{\text{col}} \) can be obtained by the properly controlled laser irradiation time after power density increment. Since the air hole collapsing are almost isolated from the elongation process, \( L_{\text{col}} \) can be precisely controlled to obtain desired extinction ratios without taper deformation. The proposed method is also effective for fine tuning of extinction ratios in air hole collapsed PCF coupler fabrications.

3. EXPERIMENTAL RESULTS

Fig. 2 shows a photograph of the PCF cross section for coupler fabrication. The PCF was polarization-maintaining PCF (PM-PCF) with two-fold rotational symmetrically in air hole arrangement. The air hole pitch was \(~5.0 \mu m\). The diameters of large and small air holes were \(~4.8 \mu m\) and \(~3.0 \mu m\), respectively. The cladding diameter was \(~123 \mu m\).

![Fig. 2: Cross section of PCF for coupler fabrication.](image)

Fig. 3 shows the setup for PCF coupler fabrication. A pulsed CO\(_2\) laser was used for coupler fabrication. The maximum value of the averaged laser power was \(~25\)W. The infrared light from the laser was irradiated to the side of fibers through two cylindrical lenses that are used for focusing the beam in radial direction to fiber and for defocusing the beam in longitudinal direction to fiber. The diameter of the irradiated laser beam was \(~1\)mm × \(~14\)mm. The fibers were fixed on the
of elongation ratio. The 27% of extinction ratio was obtained at cross port for a linearly polarized incident light at 1550nm-wavelength.

PCF couplers with air hole collapsed tapers were fabricated. The laser power density was rapidly increased at the end of elongation process as shown in Fig. 4 (black lines). The increased laser power density was more than four times as high as the power density for fiber elongation. The length of

Fig. 6: Taper transition region of PCF coupler with air hole collapsed taper.
air hole collapsed region \( (L_{\text{col}}) \) was adjusted by the irradiation time after power density increment \( (t_{\text{ irradiation}}) \). In our experiments, \( t_{\text{ col}} \) was set as several seconds. Since \( t_{\text{ col}} \) is short enough compared with the time for elongation, it is considered that the air hole collapsing is almost isolated from the elongation process. Therefore, it is expected that \( L_{\text{col}} \) (i.e. extinction ratios) can be adjusted precisely.

A PCF coupler with air hole collapsed taper was fabricated, where \( t_{\text{ col}} \) was set as \( \sim 2s \). Fig. 6(a) shows a photograph of the taper transition region side view of the fabricated air hole collapsed PCF coupler. It is found that the air holes were collapsed in the taper transition region. \( L_{\text{col}} \) was \( \sim 6mm \), i.e., the ratio \( L_{\text{col}}/L_e \) was \( \sim 0.33 \). 33% of extinction ratio at cross port was obtained at 1550nm-wavelength, where the polarization dependence of the extinction ratio was not observed.

Next, another air hole collapsed PCF coupler was fabricated, where \( t_{\text{ col}} \) was set as \( \sim 4s \). A photograph of the taper transition region side view of the fabricated PCF coupler is shown in Fig. 6(b). It is shown that the air holes were collapsed in the taper transition region similar to the result shown in Fig. 6(a). \( L_{\text{col}} \) was \( \sim 12mm \), i.e., the ratio \( L_{\text{col}}/L_e \) was \( \sim 0.67 \). It was confirmed that \( L_{\text{col}} \) could be adjusted by properly controlling \( t_{\text{ col}} \). The extinction ratio at cross port was 57%. Hence, it was demonstrated that the extinction ratio could be successfully adjusted by controlling \( L_{\text{col}} \).

The excess losses of fabricated PCF couplers were more than 5dB. This value is not low in practical use. The cutoff of fundamental mode in PCF taper [16] is considered as an origin of the loss. We think that the optimally design of the air hole arrangement and taper profile is one of the solutions to reduce excess losses of PCF couplers.

4. CONCLUSIONS

In this paper, we proposed a new method to control the length of air hole collapsed region for coupling characteristic adjustment in air hole collapsed PCF coupler. At first, the temporary variation of laser power density and fiber elongation speed were set to fabricate an air hole remaining PCF coupler using \( \text{CO}_2 \) laser irradiation. For air hole collapsing in coupler taper, the laser power density was rapidly increased at the end of elongation process, and the length of air hole collapsed region was controlled by the laser irradiation time after the power density increment. In our experiment, we set the conditions to fabricate an air hole remaining PCF with \( \sim 18mm \) tapered region. It was confirmed that the air holes in coupler taper could be collapsed by the rapid laser power density increment at the end of elongation process. The length of air hole collapsed region was controlled as \( \sim 6mm \) and \( \sim 12mm \) as the laser irradiation time after power density increment was set as \( \sim 2s \) and \( \sim 4s \), respectively. The extinction ratio was successfully adjusted from 33% to 57% by controlling the length of air hole collapsed region from \( \sim 6mm \) to \( \sim 12mm \).

In the proposed method, the laser irradiation time for air hole collapsing is short enough compared with the time for fiber elongation. Hence, it is considered that the air hole collapsing is almost isolated from the elongation process, and the length of air hole collapsed region can be precisely controlled. The proposed method is also effective for fine tuning of extinction ratios in air hole collapsed PCF coupler fabrications.

REFERENCES

