In-line Modal Couplers based on Multicore Fibers

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Keywords: Multicore Fibers, Intermodal Coupling, Fiber-optic Sensors.

Abstract: We propose an in-line modal coupler based on a multicore fiber (MCF) which can be readily fabricated by using the adiabatic tapering method. The intermodal coupling of the in-line modal coupler apparently generated the transmission oscillation of the center core and the multiple side core modes depending on the waist diameter. The reduction of the waist diameter of the adiabatically tapered MCF could dramatically change its sensitivities to strain, temperature, and ambient index. We believe that experimental results are very useful to fabricate the in-line modal coupler based on the MCF and to improve the performance of the fiber-optic sensors by controlling the waist diameter of the adiabatically tapered MCF.

1 INTRODUCTION

Multicore fibers (MCFs) with high core density and low cross talk level have attracted much attention in optical communications systems (Koshiba et al., 2009; Li et al., 2007; Zhu et al., 2010). Recently, the special properties of the MCF, such as small size, well defined core separation, and good thermal stability, have led to much interest in fiber optic sensors (Flockhart et al., 2003; Newkirk et al., 2014). Fiber Bragg gratings inscribed in a four-core MCF provides a simple technique to measure the two-axis curvature (Flockhart et al., 2003). It was reported that the MCF-based multimode interference device is capable of measuring temperature up to 1000°C (Newkirk et al., 2014). Therefore, it is important to consider the basic quantities and applications of the MCF. In this paper, we discuss transmission characteristics of an in-line modal coupler with variations in strain, temperature, and ambient index. The in-line modal coupler is successfully fabricated by adiabatically tapering the MCF with seven cores. The waist diameter of the adiabatically tapered MCF predominantly controls the strength of the evanescent field and the pitch size resulting in the transmission oscillation based on the intermodal coupling among the seven core regions. The extinction ratio of the transmission oscillation was gradually improved by diminishing the waist diameter to be ~30 μm because of the enhancement of the coupling strength among the multiple core modes. The further reduction of the waist diameter degraded the transmission oscillation of the in-line modal coupler because of the sinusoidal dependence of the normalized intensities of the center core and multiple side core modes on the coupling coefficient and the propagation distance. The reduction of the waist diameter of the adiabatically tapered MCF could dramatically change its sensitivities to strain, temperature, and ambient index. The reduction of the waist diameter of the adiabatically tapered MCF could dramatically change its sensitivities to strain, temperature, and ambient index.

2 EXPERIMENTS AND DISCUSSION

Figures 1(a) shows the scanning electron microscopy (SEM) image of the fabricated MCF, respectively. The MCF has seven Ge-doped cores surrounded by pure silica cladding. The pitch size (Λ) was measured to be ~32 μm. It is important to keep the identical size of Λ to suppress the crosstalk among the multiple cores of the MCF (Zheng et al., 2013). The core and the cladding diameters of the MCF were measured to be 10 and 125 μm, respectively. All seven cores in the MCF can accommodate a single mode. Since the cladding diameter of the MCF is exactly the same as that of the conventional SMF, an ordinary fusion splicing

Shim, Y., Hwang, J., Song, S. and Han, Y-G.
In-line Modal Couplers based on Multicore Fibers.
DOI: 10.5220/0005777501810184
In *Proceedings of the 4th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2016)*, pages 183-186
ISBN: 978-989-758-174-8

technique is readily capable of connecting the MCF with the SMF. The micro-tapering technique was exploited to fabricate the in-line modal coupler based on the MCF (Yoon et al., 2012). During softening and melting the MCF by using a computer-controlled heater, two translation stages simultaneously elongate the MCF resulting in the formation of the adiabatically tapered MCF. The temperature of the heater and the pulling speed of the two translation stages were controlled to be ~1000ºC and ~10 µm/sec, respectively. The reduction of the core diameter and the pitch size by tapering the MCF mainly induces the modal coupling from the center core region to the six side cores. It is important to investigate the effect of the waist diameter of the adiabatically tapered MCF on the modal coupling of the in-line modal coupler. We fabricated the various tapered MCFs with different diameters of 10, 20, 30, 50, 75, 125 µm. The length of the uniform waist region of all tapered MCFs was ~12 mm. Figure 1(b) shows the images of the tapered MCFs with different waist diameters measured by an optical microscope.

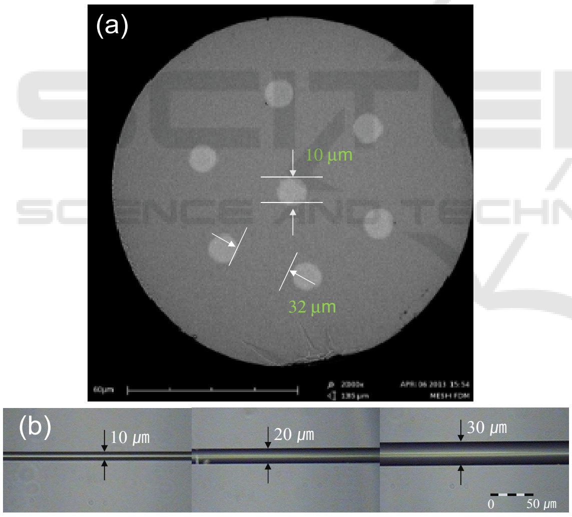

Figure 1: (a) SEM image of the fabricated MCF and (b) images of the tapered MCF measured by an optical microscope.

To investigate the effect of the waist diameter on the modal coupling, we spliced the core of the conventional SMF with the center core of the MCF and reduced the waist diameter of the MCF. We measured the transmission spectrum based on the modal coupling of the proposed in-line modal coupler with various waist diameters. Figure 2 shows the transmission spectrum of the center core mode in the in-line modal coupler. After splicing the core of the SMF with the center core of the tapered

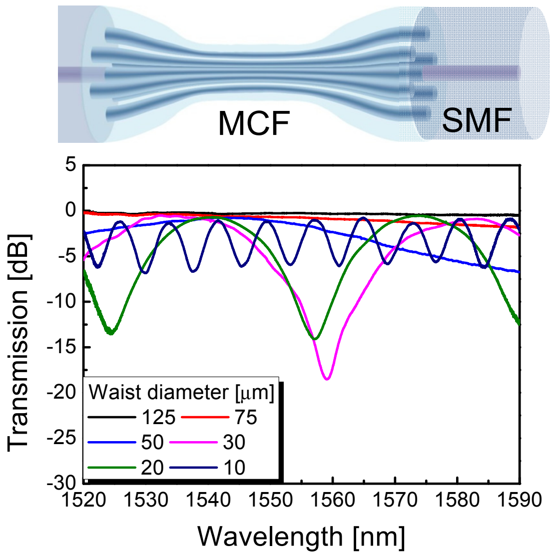

Figure 2: Experimental Results for the Transmission Spectra of the Center Core in the Proposed in-Line Modal Coupler with Various Waist Diameters.

MCF with versatile waist diameters, we measured the output of the in-line modal coupler as seen in Fig. 2. When the waist diameter was larger than ~50 µm, the modal coupling was not exhibited in the transmission spectrum of the in-line modal coupling. Since further reduction of the waist diameter improves the coupling strength among the multiple core modes in the in-line modal coupler, the periodic oscillation of the transmission spectrum was observed and the extinction ratio should be gradually increased. When the waist diameter was ~30 µm, the center core mode was sufficiently coupled to multiple side core modes. The extinction ratio of the transmission spectrum was gradually degraded by decreasing the waist diameter because the normalized intensity of the center core and multiple side core modes resulting from the modal coupling varies like $\cos^2(\sqrt{7}Cz)$ and $\sin^2(\sqrt{7}Cz)$, respectively (Chan et al., 2012). The oscillation periodicity of the transmission spectrum resulting from the modal coupling should be reduced because of the variation of the phase depending on the coupling coefficient and the waist diameter.

Figure 3(a) shows the peak wavelength shifts of the tapered MCF with various waist diameters as a function of strain. The applied strain shifted the peak wavelengths to shorter wavelength. The reduction of the waist diameter of the MCF successfully enhanced the strain sensitivity of the tapered MCF. The strain sensitivities of the tapered MCF with different waist diameters of 30, 20, and 10 µm were measured to be -0.5, -1.0, and -1.4 nm/mε,

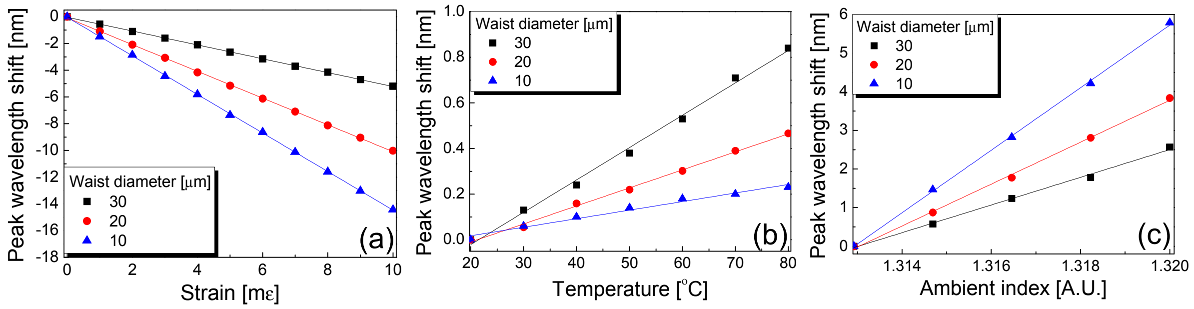

Figure 3: Peak wavelength shifts of the tapered MCFs with various waist diameters as functions of strain (a), temperature (b), and ambient index (c), respectively.

respectively. The peak wavelength of the tapered MCF was shifted to longer wavelength as temperature increased. The reduction of the waist diameter of the tapered MCF degraded its temperature sensitivity (14.2 pm/°C for 30 μm, 7.9 pm/°C for 20 μm, and 3.8 pm/°C for 10 μm) as seen in Fig. 3(b). In Fig. 3(c), the peak wavelength of the tapered MCF shifted to longer wavelength as the ambient index was increased. The ambient index sensitivity of the tapered MCF should be improved by reducing the waist diameter of the tapered MCF. The ambient index sensitivities of the tapered MCF with waist diameters of 30, 20, 10 mm were measured to be 358.6, 542.7, 809.6 nm/RIU, respectively.

3 CONCLUSIONS

In conclusion, we discussed transmission characteristics of an in-line modal coupler based on the adiabatically tapered MCF with variations in strain, temperature, and ambient index. By controlling the waist diameters, we investigated the sensitivity variation of the adiabatically tapered MCF to strain, temperature, and ambient index changes. The reduction of the waist diameter improved the coupling strength among the multiple core modes in the in-line modal coupler because of the variation of the evanescent field and the pitch size. The modal coupling of the in-line modal coupler apparently generated the transmission oscillation of the center core and the multiple side core modes depending on the waist diameter. The extinction ratio of the transmission oscillation was gradually improved by diminishing the waist diameter to be ~30 μm because of the enhancement of the coupling strength among the multiple core modes. The further reduction of the waist diameter degraded the transmission oscillation of the in-line modal coupler because of the sinusoidal dependence of the normalized intensities of the center core and multiple side core modes on the coupling coefficient and the propagation distance. The reduction of the waist diameter of the adiabatically tapered MCF could dramatically change its sensitivities to strain, temperature, and ambient index. We believe that experimental results are very useful to fabricate the in-line modal coupler based on the MCF and to improve the performance of the fiber-optic sensors by controlling the waist diameter of the adiabatically tapered MCF.

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