All-fiber Mach-Zehnder type interferometers formed in photonic crystal fiber

Hae Young Choi, Myoung Jin Kim, and Byeong Ha Lee

Department of Information and Communications
Gwangju Institute of Science and Technology
1 Oryong-dong, Buk-Gu, Gwangju, 500-712, Korea
leebh@gist.ac.kr

Abstract: We propose simple and compact methods for implementing all-fiber interferometers. The interference between the core and the cladding modes of a photonic crystal fiber (PCF) is utilized. To excite the cladding modes from the fundamental core mode of a PCF, a coupling point or region is formed by using two methods. One is fusion splicing two pieces of a PCF with a small lateral offset, and the other is partially collapsing the air-holes in a single piece of PCF. By making another coupling point at a different location along the fiber, the proposed all-PCF interferometer is implemented. The spectral response of the interferometer is investigated mainly in terms of its wavelength spectrum. The spatial frequency of the spectrum was proportional to the physical length of the interferometer and the difference between the modal group indices of involved waveguide modes. For the splicing type interferometer, only a single spatial frequency component was dominantly observed, while the collapsing type was associated with several components at a time. By analyzing the spatial frequency spectrum of the wavelength spectrum, the modal group index differences of the PCF were obtained from $2.83 \times 10^{-3}$ to $4.65 \times 10^{-3}$. As potential applications of the all-PCF interferometer, strain sensing is experimentally demonstrated and ultra-high temperature sensing is proposed.

©2007 Optical Society of America

OCIS codes: (060.2310) Fiber optics; (060.2370) Fiber optic sensors; (060.2340) Fiber optics components; (230.3990) Microstructure devices.

References and links

1. T. A. Birks, J. C. Knight, and P. St. J. Russell, “Endlessly single-mode photonic crystal fiber,” Opt. Lett. 22, 961-963 (1997).
2. J. C. Knight, T. A. Birks, R. F. Cregan, P. St. J. Russell, and J. -P. de Sandro, “Large mode area photonic crystal fibre,” Electron. Lett. 34, 1347-1348 (1998).
3. D. Mogilevtsev, T. A. Birks, and P. St. J. Russell, “Group-velocity dispersion in photonic crystal fibers,” Opt. Lett. 23, 1662-1664 (1998).
4. A. Ferrando, E. Silvestre, J. J. Miret, J. A. Monsorui, M. V. Andrés, and P. St. J. Russell, “Designing a photonic crystal fibre with flattened chromatic dispersion,” Electron. Lett. 35, 325-327 (1999).
5. G. Renvoize, B. Kuhlme, and R. McPhedran, “Dispersion management with microstructured optical fibers: ultraflattened chromatic dispersion with low losses,” Opt. Lett. 28, 989-991 (2003).
6. B. H. Lee, and J. Nishii, “Dependence of fringe spacing on the grating separation in a long-period fiber grating pair,” Appl. Opt. 38, 3450-3459 (1999).
7. S. Lacroix, F. Gonthier, R. J. Black, and J. Bures, “Tapered-fiber interferometric wavelength response: the achromatic fringe,” Opt. Lett. 13, 395-397 (1988).
8. S. Laloch, T. A. Birks, and P. St. J. Russell, “Mach-Zehnder interferometer formed in a photonic crystal fiber based on a pair of long-period fiber gratings,” Opt. Lett. 29, 346-348 (2004).
9. J.1 Villatoro, V. P. Minkovich, and D. Monzón-Hernández, “Compact modal interferometer built with tapered microstructured optical fiber,” IEEE Photon. Technol. Lett. 18, 1258-1260 (2006).
10. V. P. Minkovich, J. Villatoro, D. Monzón-Hernández, S. Calixto, A. B. Sotsky, and L. I. Sotskaya, “Holey fiber tapers with resonance transmission for high-resolution refractive index sensing,” Opt. Express 13, 7609-7614 (2005).
11. Y.-G. Han, S. B. Lee, C.-S. Kim, J. U. Kang, U.-C. Paek, and Y. Chung, “Simultaneous measurement of temperature and strain using dual long-period fiber gratings with controlled temperature and strain sensitivities,” Opt. Express 11, 476-481 (2003).
1. Introduction

Photonic crystal fiber (PCF) has been widely studied owing to its potential for realizing special optical fibers having unique properties. A PCF is generally composed of a single material with an array of air-holes running along its length. By simply removing the air-hole at the center, the core of the PCF is made. Since the structure of the air-holes could be adjustable, many unique properties such as single mode operation over a wide wavelength range [1], very large mode area [2], and unusual dispersion [3-5] have been obtained with PCFs. These properties, being desirable in several applications, make the PCF an attractive alternative for conventional fibers.

Based on conventional single mode fibers, lots of works regarding fiber interferometers have been reported [6, 7]. Recently, the fiber interferometers based on PCF were reported. The PCF interferometer utilizing a pair of long-period fiber gratings (LPGs) or having a tapered zone has been proposed [8-10]. They have demonstrated that all-PCF interferometers were suitable for sensing applications such as very high temperature and strain monitoring.

In this study, we propose simple but very effective methods that enable fabrication of all-PCF interferometers. By utilizing the cladding modes of a PCF, we can make interference between the core and cladding modes of the PCF. To excite cladding modes or to couple the core mode to cladding modes, two methods are proposed. The first method is fusion splicing two pieces of a PCF with a small lateral offset at a point. The other method is partially collapsing the air-holes of a single piece of PCF at a limited region. In both methods, a part of the fundamental core mode of a PCF can be coupled to a single or several cladding modes of the PCF. The coupled cladding modes can be re-coupled to the core mode by placing another coupling point or region at a different location along the PCF. By placing two coupling points in series, a very simple all-fiber Mach-Zehnder interferometer can be implemented. The distance between the coupling points corresponds to the physical length of the interferometer. Multiplying it with the effective index of each excited mode gives the optical path length of the corresponding arm of the interferometer. When only one cladding mode is excited, we will have the interferometer having two arms; whose physical lengths are exactly the same but the optical lengths are different to each other due to the difference in effective indices. In the LPG pair based interferometer [6], only one cladding mode is involved at a wavelength owing to the high wavelength selectivity of LPGs. However, in the proposed PCF interferometers based on splicing or collapsing of PCF, a more complicated interference phenomenon is expected due to the possibility of more than two arms arising from multiple cladding modes being excited.

The interference fringe patterns of the proposed all-PCF interferometers are measured as a function of wavelength. By taking the Fourier transform of the wavelength spectrum, the spatial frequency spectrum of it is obtained and used to analyze the spectral response of the interferometer. The spectrum is investigated with respect to the physical length of the interferometer and the involved waveguide modes also. By analyzing the spectrum, the modal group index difference between the core and the corresponding cladding mode of the PCF is calculated. Finally, the potential applications of the proposed interferometer are presented. As a longitudinal strain sensor, it was observed that the interference fringe shifted linearly toward the shorter wavelength direction with a sensitivity of ~2.2 pm/με. As a temperature sensor, it will be very powerful especially at high temperature since the PCF itself is composed of only fused silica. The diffusion problem of a conventional fiber or the erasing problem of fiber gratings will not happen with the all-PCF sensor.
2. Fabrication and properties of all-PCF interferometers

Figure 1 shows the schematics of the proposed techniques and the cross sectional view of the PCF used for the experiment. The PCF (LMA-10 of Crystal Fiber Co.) designed to be endless single mode has 4 layers of air-holes around a solid core of a diameter 11 ± 1 μm.

In order to make an interferometer by the splicing method, a piece of PCF was fusion spliced at both ends with small intentional lateral offsets. As depicted in Fig. 1(a), it is expected that, at a spliced point, a part of the core mode beam is coupled to several cladding modes of the middle PCF, and then coupled back to the core mode at the other point. The re-coupled beam makes interference with the beam that has propagated only as the core mode without being affected by the splicing.

![Schematics of the interferometers based on (a) splicing and (b) collapsing methods, and (c) the cross sectional view of the PCF. The insets are microscope images of the coupling points. A small lateral offset was intentionally induced in (a) while fusion splicing. In (b), only collapsing was made without cleaving and splicing.](image)

In the splicing scheme, the important parameters affecting the performance and the properties of the interferometer are listed as the physical length of the PCF in the middle, the amount of lateral offset, and the discharge arc conditions for fusion splicing. The first two conditions were quantitatively under control; however, the last one was not. Unfortunately, since the absolute arc-power and arc-time were not supported by the fusion splicer (S183PM, FITEL co.), only the relative values were available in the experiment. After several trial and errors, the optimum arc-power and arc-time suitable for getting a high fringe contrast and a low excess loss were found to be 90 units and 200 ms, respectively. At these optimum splicing conditions, when the lateral offset was 3 μm, the splicing loss was as small as 2 dB. It must be pointed out that the splicing loss could be reduced by decreasing the offset, but it would reduce the fringe contrast due to reduction in the coupling ratio. Although the splicing method is very simple, it still requires tiresome cleaving and fusion splicing procedures. Furthermore, the use of fusion splicing weakens the strength of the fiber, which limits its usage as a strain sensor. To overcome these problems, the second method based on collapsing the air-holes in a single piece of PCF is devised.

As shown in Fig. 1(b), the air-holes of a single piece of PCF were collapsed at two regions along the PCF by using the electric arc of the same fusion splicer. At the region where the air hole structure is collapsed, the PCF is not a single mode fiber anymore since the fiber has no cladding part. Therefore, some parts of the beam that has been originally in the core mode can be coupled to several cladding modes. The inset in Fig. 1(b) shows that the air-holes were fully collapsed by the arc discharging and the collapsing length was about 300 μm. Compared with the splicing method, the collapsing method is much simpler. It does not need any troublesome cleaving or aligning process. However, the measured loss was around 5 dB (±0.5 dB), which was bigger than that of the splicing method.
The transmission or the wavelength spectra of the fabricated interferometers were measured with several interferometer lengths and shown in Fig. 2. The light source used for the measurements was a broadband LED, which center wavelength was about 1535 nm. The LED had a Gaussian-like smooth spectral shape with a FWHM (full-width at half maximum) of around 50 nm. To see the interference pattern more clearly, the huge DC term was removed from the original raw spectrum. At first, the transmission spectrum of the LED was measured prior to making the interferometer and stored. Then, the stored LED spectrum was subtracted from the measured spectrum. Finally, the DC level of the spectrum was adjusted to have zero average. The optical spectrum analyzer had a 0.1 nm spectral resolution.

Figures 2(a), 2(b), and 2(c) are the transmission spectra obtained with the splicing type interferometer (Fig. 1(a) case). Highly uniform interference fringes were observed over the available whole spectral range, and the fringe spacing became finer with increasing of the interferometer length. Figures 2(d), 2(e), and 2(f) are the spectra for the collapsing type interferometer (Fig. 1(b) case). It is noteworthy that the collapsing case gave better fringe contrast than the splicing one; however, its interference fringe was not uniform but looked like having several frequency components in the interference fringe periods.
Fig. 3. The spatial frequency spectra of the proposed interferometers measured at several interferometer lengths. The splicing method (a) gave just one dominant spatial frequency, while the collapsing method (b) induced several spatial frequencies.

The wavelength spectra in Fig. 2 were Fourier transformed to get the spatial frequency spectra of the interference fringes. Interestingly, as shown in Fig. 3(a), the splicing type interferometer had only one dominant peak in the spatial frequency spectra for all interferometer lengths. Even though a tiny second peak was observed at certain separations, the peak was very feeble. On the other hand, the collapsing type had several peaks in moderate strengths. As the interferometer length increased, the spatial frequency of each peak increased in both types; however, the relative intensity of each peak was not well preserved.

The variations of spatial frequencies (peaks in Fig. 3) were measured in terms of the interferometer length and shown in Fig. 4. All distinguishable and consistent peaks in Fig. 3 were counted. In the figure, each straight line is the linear curve fitting to the group of data points that were resulted from the interference with the same order of cladding mode. With the Fig. 4(a), due to the dominant single peak in Fig. 3(a), it is clear that the spatial frequency increases linearly with the interferometer length. Since the upper curve has a higher spatial frequency than the lower one at a separation, we can say that the upper data was resulted from a higher order cladding mode. In the same manner, with Fig. 4(b), we can say that the collapsing method excited many cladding modes. The slope of each line is related with the difference of the effective group indices between the fundamental core mode and the excited cladding mode. In general, the higher order mode has the lower effective index in a waveguide, thus, gives a steeper fitting line. The detail on these matters is followed.

Fig. 4. Variations of the spatial frequencies for the splicing method (a) and the collapsing method (b) plotted in terms of the interference length. Each straight line is the fitted linear curve only for the group of data points resulted from the same order of cladding mode.
3. Discussion
From the wavelength spectrum in Fig. 2 and its spatial frequency spectrum in Fig. 3, we can say that the splicing type interferometer exhibits only one dominant spatial frequency for all interferometer lengths [Fig. 3(a)]. The second peak was very small for most of lengths; at some lengths it was not discernable. Even when the offset distance was increased up to 5 μm, interestingly, no other dominant peak was observed. The feeble second peak means that the coupling dominantly occurred between the fundamental core mode and only one cladding mode of the PCF. On the other hand, as shown in Fig. 3(b), several higher order cladding modes were excited for the collapsing type interferometer. Theoretically, the proposed interferometer has no mechanism preventing the mode coupling to certain order of modes. However, considering the symmetry and amount of the perturbation made on the fiber, we can think of dominant modes to which the mode coupling happens easily. In general, an optical fiber is designed for guiding the core mode not the cladding modes. Therefore, the coupled cladding mode has appreciable propagation loss and is easily affected by the micro/macro bending and/or contamination on the fiber surface.

The exact reason for the low coupling efficiency, even with a larger offset, to higher order cladding modes in the splicing type interferometer requires further study and investigation on the cladding modes of the PCF. However, we believe that the large offset in the core of a fiber was not effectively big enough for the cladding mode due to a relatively large cladding diameter of the fiber. On the other hand, in the collapsing method, as shown in the inset of Fig. 1(b), the air-hole structure was completely collapsed. Thus, coupling into many cladding modes were possible due to appreciable diffraction of the core mode beam at the collapsing region. Decreasing the amount or/and controlling the length of collapsing is thought to limit the number of excitable cladding modes or/and increase the visibility of the interference fringe.

As mentioned, the interference depends on the optical path length difference between the two arms of an interferometer. In general, a cladding mode has a lower effective index than the core mode, and a high order cladding mode has a smaller effective index. Therefore, since the physical lengths of our interferometer arms are exactly the same, the spatial frequency of the wavelength spectrum is directly related with the effective indices difference between the core mode and the involved cladding mode.

The interference between the core mode and a cladding mode of the proposed interferometer is given as a function of the core mode intensity $I_{\text{core}}$, the cladding mode intensity $I_{\text{clad}}$, and the phase difference $\phi$ accumulated during a physical length $L$ [6];

$$I_{\text{total}} = I_{\text{core}} + I_{\text{clad}} + 2\sqrt{I_{\text{core}}I_{\text{clad}}} \cos \phi,$$

with

$$\phi = k \Delta n_{\text{eff}} L .$$

Where, the differential effective index $\Delta n_{\text{eff}}$ was defined as

$$\Delta n_{\text{eff}} \equiv n_{\text{eff}}^{\text{core}} - n_{\text{eff}}^{\text{clad}} .$$

Since the spectrum of Fig. 2 was taken as a function of wavelength, we need to express Eq. (2) with the center wavelength $\lambda_0$ and the deviation from it, $\Delta \lambda$ ($\Delta \lambda \equiv \lambda - \lambda_0$). Taylor expanding of the wave number $k$ at the center wavelength in Eq. (2) and taking only the first order term gives

$$\phi = \phi_0 - \frac{2 \pi \Delta \lambda}{\lambda_0} \Delta n_{\text{eff}} L .$$
The phase is linearly proportional to the wavelength deviation $\Delta \lambda$ and the interferometer length $L$. However, Eq. (4) is valid only when the dispersion of the guided mode is negligible. In general, the effective index of a guided mode depends on both the material dispersion and the waveguide dispersion of the waveguide. Thus, to be more general, the differential effective index in Eq. (4) should be replaced with the differential modal group index [6], which gives

$$\phi = \phi_0 - \frac{2\pi \Delta \lambda}{\lambda_0} \Delta m_{\text{eff}} L ,$$

with

$$\Delta m_{\text{eff}} = \Delta n_{\text{eff}} - \lambda_0 \frac{\partial}{\partial \lambda} \Delta n_{\text{eff}} .$$

While, the spatial frequency spectrum of Fig. 3 was obtained by taking the Fourier transform of the spectrum in Fig. 2. Thus, a peak in the spatial frequency spectrum corresponds to a sinusoidal interference pattern represented mathematically as

$$\cos(2\pi \xi \Delta \lambda).$$

Combining this with Eq. (5) gives the differential modal group index as a function of the controllable interferometer length $L$ and the measurable spatial frequency $\xi$;

$$\Delta m_{\text{eff}} = \frac{\lambda_0^2 \xi}{L} .$$

Or, we have

$$\xi = \frac{1}{\lambda_0^2} \Delta m_{\text{eff}} L .$$

The spatial frequency is given proportional to the interferometer length $L$, which explains why the data sets in Fig. 4 were well fitted with linear curves. As mentioned, the different lines in Fig. 4 were resulted from the interference with different cladding modes. In the same way, the spatial frequency is proportional to the differential modal group index $\Delta m_{\text{eff}}$, which gives the slope of the linear curve in Fig. 4. Since the higher order cladding mode has the lower effective index, or higher differential effective index, we can say that the upper curve was resulted from the interference with the higher order cladding mode.

With the dominant peak in the spatial frequency spectrum of the splicing type interferometer, the lower curve in Fig. 4(a), the differential group index was clearly calculated as $\Delta m_{\text{eff}} = 2.83 \times 10^{-3}$. While, the upper curve gave $3.48 \times 10^{-3}$. The similar calculations were made with the collapsing type interferometer given by Fig. 4(b), and got the differential modal group indices ranged from $3.30 \times 10^{-3}$ to $4.65 \times 10^{-3}$.

As shown in Fig. 3(b), the spatial frequency spectrum had many peaks, which means many cladding modes were involved in the interference. Therefore, we can say that studying the PCF interferometers might be helpful to understand the cladding modes of a PCF or the light propagation in the cladding region of the PCF. The PCF itself had six-fold symmetry in its air-hole structure and the lateral offset in the splicing method gave asymmetry in the mode coupling. These symmetry matters make the analysis more complicated. Furthermore, since the PCF was not intentionally designed for guiding the cladding modes as mentioned, the propagating loss of each cladding mode should be considered. To get the full understanding, first of all, we need to improve the experimental accuracy. Expanding the wavelength range of the input beam by using a wideband light source is one of the means that can improve the accuracy of the experiment.
4. Potential applications

Optical fiber sensors measuring physical parameters such as strain, refractive index and temperature are attractive owing to their compact size and high sensitivity [10-13]. To investigate the usefulness of the proposed interferometers as a strain sensor, the interferometer based on the collapsing method was utilized.

A 12 cm long interferometer was fabricated and the transmission spectrum was monitored while applying longitudinal strain. The PCF having the interferometer was fixed at a point and at another point, separated by 18 cm from the first one; it was dragged with a micrometer whose minimum scale was 10 μm. Thus, the error in applying strain was about ±30 με. Figure 5 shows the spectra measured without strain (black line) and with 1730 με strain. Interestingly, the spectrum moved toward the short wavelength direction or was blue shifted. At two wavelengths in its spectrum, centered at 1487 nm and 1560 nm, the strain-induced variations of the interference fringes were measured with small steps and plotted in Fig. 6. Both interference peaks were linearly blue shifted with increasing of the strain. However, the sensitivities were lightly different; –2.16 pm/με at 1487 nm and –2.28 pm/με at 1560 nm. This discrepancy might be resulted from the dispersion of the PCF modes. The hysteresis of the measurement was within the measurement error. In both graphs, the data points look like oscillating across the fitting linear curves. If it was not due to measurement error, the oscillation might be resulted from the competition of several cladding modes. The effective index of each mode might have a different dependency on strain. Further accurate measurement and more aggressive analysis are under preparation.

![Fig. 5. Transmission spectra of the interferometer measured at 0 and 1730 με strain. The interferometer based on the collapsing method and having a 12 cm length was utilized. The interference fringe was shifted toward the shorter wavelength direction with the strain.](image)

The blue shift of the transmission spectrum with increasing of the strain is opposite to that of the strain sensors based on conventional single mode fibers [11, 12]; however, it is the same as the case of a long period fiber grating inscribed in PCF [14]. Careful studies on the geometrical dependency of the effective index, modal dispersion, and the elasto-optic property of the PCF material are necessary to get full understanding about the blue shift.
Fig. 6. The strain responses of the interference peaks centered at 1487 nm (a) and 1560 nm (b), respectively. The straight lines are the linear fits. The strain sensitivities were $-2.16 \text{ pm/}\mu\text{e}$ at 1487 nm (a) and $-2.28 \text{ pm/}\mu\text{e}$ at 1560 nm (b).

Although experiment was not made due to lack of instrument, the proposed all-PCF interferometer has great potential as an ultra-high temperature sensor. Since the PCF can be made of temperature resistance single material, fused silica in our case, the sensor can withstand high temperature. The diffusion of doped materials at high temperatures, which happens with a conventional fiber, will not happen with the PCF because the PCF does not include any dopant. For the case of sensors based on fiber gratings, the grating has the tendency of being erased at high temperatures and the mode coupling is highly sensitive to wavelength. However, the PCF sensor is not erased and the coupling does not depend on wavelength. The wavelength insensitivity of the proposed interferometer allows us to have a wavelength spectrum over a broad wavelength range, so that we have much freedom in the operating wavelength.

5. Conclusions

We have demonstrated simple but very effective fabrication methods that enabled us to implement compact in-line all-PCF Mach-Zehnder interferometers. By invoking interference between the core mode and the cladding modes of a PCF, the all-PCF interferometer could be implemented. To excite the cladding modes from the core mode of a PCF, two methods have been tried. The first method was splicing two pieces of a PCF with a small lateral offset and the other was collapsing the air-holes of a single PCF piece without any cleaving or aligning process. The interferometer was completed by making these coupling points at two separated locations along the PCF. Experimentally, it was observed that the splicing method activated only one cladding mode appreciably while the collapsing method activated several cladding modes at the same time. The spatial frequency of the wavelength spectrum was linearly proportional to the physical length of the interferometer and the modal group index difference between the fundamental core mode and the involved cladding mode. By analyzing the spatial frequency spectra of the proposed all-PCF interferometer, the differential modal group indices of the PCF were obtained. They were ranged from $2.83\times10^{-3}$ to $4.65\times10^{-3}$. The obtained information regarding the modal group indices of a PCF might be helpful to understand or investigate the cladding modes of the PCF.

The potential application of the interferometer as a strain sensor was experimentally demonstrated. The interference fringe was linearly shifted toward the shorter wavelength direction with increasing strain. The strain sensitivity was $-2.2 \text{ pm/}\mu\text{e}$. Another potential application can be found in ultra-high temperature sensing. Since the PCF is composed of only temperature-resistant fused silica, we can expect a good performance up to over 1500°C. Especially, since the collapsing method does not need any cleaving or fiber aligning process it is extremely simple and the implemented device becomes robust, so that we might be able to
find many other useful applications mainly in sensor field.

Acknowledgments

This work was supported in part by Korea-Italy Joint Research Project, and by the Korean Ministry of Education (MOE) through the BK-21 Project.