Large temperature sensitivity of Sagnac loop interferometer based on the birefringent holey fiber filled with metal indium

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Abstract: The large temperature sensitivity of the Sagnac loop interferometer based on the birefringent holey fiber filled with metal indium was experimentally demonstrated. The temperature sensitivities of the wavelength shift of the interferometer and the birefringence of the fiber were measured to be −6.3 nm/K and −3.3×10⁻⁶/K, respectively. The large temperature sensitivity of the fiber was explained by introduction of the fiber birefringence change originated from the large thermal expansion property of the metal indium at the elevated temperature.

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1. Introduction

Sagnac loop interferometers (SLIs) based on birefringent optical fibers are recently receiving considerable attention for fiber-optic wavelength-division-multiplexing (WDM) filter and...
sensor implementation because they have attractive features such as, the simplicity in the optical structure, the insensitivity to the input polarization state, the large wavelength tunability, and the high extinction ratio [1]. Thermal property of the birefringent fibers is critical for the fiber-optic device applications in desiring the high functionalities. Up to the present, the thermal properties of the SLIs have been extensively studied with the various birefringent fibers [2-7]. The birefringent photonic crystal fibers (PCFs) exhibited the extremely small temperature sensitivity of the birefringence, \( \frac{dB}{dT} = -7.0 \times 10^{-9} / \text{K} \) [2], and the wavelength shift sensitivity, \( \frac{d\lambda}{dT} = -0.3 \text{ pm/K} \) [3]. The small temperature sensitivity of the fibers is attributed to the matched thermal property between the core and the cladding that are made of the same silica glass. The small sensitivity makes the fibers promising elements for fiber-optic devices with the excellent temperature stability [2,3].

For temperature sensing applications, on the other hand, the large sensitivity on temperature is desired in the fibers. In the SLI made by the conventional birefringent fiber (Fibercore, HB1000) with the circular core and the stress inducing cladding, the very large temperature sensitivity of the birefringence (\(-7.5 \times 10^{-7} / \text{K}\)) and the wavelength shift sensitivity (\(-1.0 \text{ nm/K}\)) was demonstrated [4]. More recently, the large temperature sensitivities of the birefringence (\(-2.7 \times 10^{-7} / \text{K}\)) in the holey fiber with an elliptical core [5] and the wavelength shift sensitivity (\(-1.9 \text{ nm/K}\)) in the birefringent PANDA fiber (ThorLabs, PM-1550-HP) [6] were observed. Even though the temperature sensitivity of the SLIs is one or two order of magnitude larger than those of the fiber Bragg gratings (\(d\lambda/dT = 0.01 \text{nm/K}\)) or the long period gratings (\(d\lambda/dT = 0.1 \text{nm/K}\)) [4,8], the sensitivity is generally limited by the difference in the thermal expansion properties of the glasses between the stress inducing region and the others [9].

In this work, we investigated the temperature sensitivity in the new class of birefringent fiber with the elliptical core and the holes filled with metal indium (In). Indium was expected to induce the very large thermal stress since the thermal expansion coefficient of the metal is at least one order of magnitude larger than that of the fiber material (glass) [10]. As a result, the very large temperature sensitivity of the birefringence, \(-3.3 \times 10^{-6} / \text{K}\), and the wavelength shift sensitivity, \(-6.3 \text{ nm/K}\), were found in the SLI based on the fiber and they are larger than the largest value reported [4].

2. Experiments

2.1 Fabrication of the birefringent holey fiber filled with indium

An optical fiber preform with a germanium doped core was fabricated by the conventional modified chemical vapor deposition process. The refractive index difference between the core and the cladding of the prefrom was \(\sim 0.018\). Two holes beside the core of the preform were made by the mechanical drilling and the prefrom was drawn into the birefringent holey fiber with the diameter of 125 \(\mu\text{m}\) using the fiber drawing process. The drawing temperature and the drawing speed were properly controlled to make the elliptical core by slightly collapsing the holes to the diameter of \(\sim 20 \mu\text{m}\) during the drawing process.

Molten indium at 180 °C was injected into the holes of the fiber by the aid of the nitrogen gas at the gas pressure of 25 bar [11,12] to introduce the large thermal mismatch with silica glass (\(\alpha = 5.5 \times 10^{-7}\)) used for the fiber cladding. Note that the thermal expansion coefficient and the melting temperature of indium were \(\alpha = 32.1 \times 10^{-6}\) and 156 °C, respectively [10].

Fig. 1 (a)-(d) show the cross-sectional micro-photo images and the SEM images of the fiber before and after filling the metal indium into the holes of the fiber. The elliptical core was found at the center of the fiber and the metal was well incorporated by fully filling the holes almost without a gap between the metal and the glass.

2.2 Measurement of the temperature sensitivity of the SLI based on the fiber

The temperature sensitivity of the birefringent holey fiber filled with indium was investigated by measurement of the transmission characteristics of the SLI at different temperatures. The
100 cm-long birefringent fiber was fusion spliced to the single mode fiber arm of the SLI made by the 3 dB fiber coupler and the polarization controller as shown in Fig. 1(e). The central part with the 20 cm-long internal metal and the 30 cm-long side parts without the metal in the holey fiber was heated at the temperature range between 27 and 115 °C by use of the heating chamber. Then the broad-band light source (ThorLabs, SOA 240) was injected into the fiber and the transmission spectrum of the SLI was measured by the optical spectrum analyzer (Ando, AQ 6317B). The PC was used to maximize the interference contrast in the transmission spectrum of the SLI.

3. Temperature sensitivity of the holey fiber filled with metal

The transmission of the SLI based on the birefringent holey fiber is given by the birefringence induced phase difference, \( \phi \), between the two principal polarization modes of the fiber core, \( T = \sin^2(\phi/2) \). The phase difference is the function of the birefringence, \( B \), the wavelength, \( \lambda \), and the length, \( L \), of the fiber and is expressed as \( \phi = 2\pi BL/\lambda \). The birefringence is inversely proportional to the fringe spacing, \( \Delta \lambda \), of the interference in the transmission and the fiber length [1,3],

\[
B = \frac{\lambda^2}{L\Delta\lambda}.
\]  

(1)

In the fiber system shown in Fig. 1(b), the product of the birefringence and the length can be divided into the local fiber regions using Eq. (1) and is expressed as

\[
\frac{\lambda^2}{\Delta\lambda} = BL = B_mL_m + B_nL_n + B_0L_0, \quad L=L_m+L_n+L_0=100cm,
\]

(2)

where \( B_mL_m \) (\( L_m=20cm \)) and \( B_nL_n \) (\( L_n=60cm \)) are the products for the fiber regions with and without the metal inside the heating chamber, respectively, and \( B_0L_0 \) (\( L_0=20cm \)) is the product for the fiber region without the metal outside the chamber. Therefore, the birefringence in the region with the metal of the holey fiber at the varied temperature, \( T \), is expressed as

\[
B_m(T) = \frac{L(T)}{L_m(T)} B(T) - \frac{L_n(T)}{L_m(T)} B_n(t) = \frac{L_0}{L_m(T)} B_0 \approx \frac{\lambda^2}{L\Delta\lambda(T)} \bigg|_m - 3B_n(T) - B_0.
\]

(3)

As a reference, the birefringence in the region without the metal of the holey fiber can be obtained using the SLI totally made by the holey fiber without the metal,

\[
B_n(T) = \frac{L(T)}{L_n(T)} B(t) - \frac{L_0(T)}{L_n(T)} B_0 \approx \frac{\lambda^2}{4L\Delta\lambda(T)} \bigg|_n = -\frac{1}{4}B_0, \quad L_n=L_m+L_0=80cm.
\]

(4)

The variation of the fiber length owing to the thermal expansion was ignored in the equations.

Fig. 1. Micro-photo images of the birefringent holey fiber (a) without and (b) with the metal indium, (c) SEM image of the fiber with the metal indium, (d) magnified SEM image of the metal indium inside the hole of the fiber, and (e) schematic setup to measure the temperature sensitivity of the SLI based on the fiber.
In the fiber system shown in Fig. 1(b), the total phase difference is given by the sum of the phases of the local fiber regions with and without the metal and expressed as,

\[ \phi(T) = 2\pi b L / \lambda = \phi_n(T) + \phi_m + \phi_0 . \]

Using Eq. (1), thus, the phase change sensitivity of the local fiber region with the metal is represented by

\[ \frac{1}{L_m} \frac{d\phi_m}{dT} = \frac{1}{L_m} \left[ \frac{2\pi}{\Delta \lambda} \frac{d\lambda}{dT} \right]_m - \frac{d\phi_n}{dT} . \]  

(5)

In the equation, the temperature differentiated phase term, \( d\phi_n /dT \), for the local fiber region without the metal can be obtained using the reference SLI without the metal. The phase change sensitivity of the holey fiber without the metal is expressed as

\[ \frac{1}{L_p} \frac{d\phi_p}{dT} = \frac{1}{L_p} \left[ \frac{2\pi}{\Delta \lambda} \frac{d\lambda}{dT} \right]_n . \]  

(6)

4. Results and discussion

Figure 2 shows the transmission spectra of the SLI based on the fiber with and without metal indium at the temperatures ~27 and 109 °C. The periodic interference fringe is the characteristic transmission of the SLI. In the SLI without the metal, the fringe spacing was 19.75 nm at the temperature, 27 °C. In the case with the metal, on the other hand, the fringe spacing strongly decreased to 11.77 nm. At the temperature of 109 °C, the fringe spacing slightly increased to 20.53 and 18.81 nm for the cases without and with the metal, respectively.

![Transmission spectra of the SLI based on the holey optical fiber with and without the metal indium at the temperatures ~27 and 109 °C.](image)

Fig. 2. Transmission spectra of the SLI based on the holey optical fiber with and without the metal indium at the temperatures ~27 and 109 °C.

Using Eqs. (3) and (4), the birefringence of the fiber with and without the metal indium was investigated from the fringe spacing and the result was summarized in Table 1. The birefringence at ~27 °C strongly increased more than 4 times by incorporation of the metal. The large increase of the birefringence in the case with the metal is explained by the very large thermal expansion property of indium used as the stress inducing material in the fiber. In both cases with and without the metal, the birefringence decreased with the increase of the

<table>
<thead>
<tr>
<th>Temp.</th>
<th>~27 °C</th>
<th>~109 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>fringe spacing</td>
<td>birefringence</td>
<td>fringe spacing</td>
</tr>
<tr>
<td>without indium</td>
<td>19.75 nm</td>
<td>9.09×10^-5</td>
</tr>
<tr>
<td>with indium</td>
<td>11.77 nm</td>
<td>3.99×10^-4</td>
</tr>
</tbody>
</table>

Table 1. Fringe spacing and birefringence of the birefringent holey fiber with and without the metal indium at the temperatures of 27 and 109 °C, approximately.
temperature and this agrees with the negative temperature sensitivity of the birefringence found in the previous reports studied with the various birefringent fiber structures [3-6].

The transmission spectra of the SLI without the metal indium at the different temperatures between 39.1 and 55.3 °C were presented in Fig. 3(a). The interference fringe shifted about 10.7 nm to the shorter wavelength during the temperature increase from 39.1 to 55.3 °C. The spacings of the periodic interference fringes near the wavelength of 1350 nm were 19.85 and 20.07 nm at 39.1 and 55.3 °C, respectively. Fig. 3(b) shows the magnitude of the wavelength shift of the fringe in the temperature from 27 to 115 °C. During the initial temperature increase from 26.7 to 35.1 °C, the fringe shifted to the longer wavelength and turned to the shorter wavelength at the higher temperature. In the temperature above 35.1, the fringe monotonously shifted to the shorter wavelength at the rate of \(d\lambda/dT = -0.61 \text{ nm/K}\). The negative wavelength shift originates from the decrease in the birefringence and it was also found in the previous studies [3-6]. The red shift below 35.1 °C is believed to be due to the dominant fiber elongation effect possibly resulted from the structural change of the fiber coating material in comparing with the decrease in the birefringence [3].

![Fig. 3. (a) Transmission spectra of the SLI based on the holey fiber without the metal indium at the different temperatures (The dashed line indicates the guide to show the wavelength shift.) and (b) wavelength shift of the fringe with the temperature in the SLI (The solid line represents the linear fit for the wavelength shift in the temperature range, 35.1-112.2 °C).](image)

In the SLI with the metal, the magnitude of the negative wavelength shift strongly increased. Figure 4(a) shows the transmission spectra of the SLI with the metal at the elevated temperatures from 38.4 to 46.5 °C. The interference fringe shifted about 51.6 nm to the shorter wavelength with the temperature increase from 38.4 to 46.5 °C. In addition, the wavelength shift showed the high linearity in the all temperature range from 27 to 115 °C as shown in Fig.

![Fig. 4. (a) Transmission spectra of the SLI based on the holey fiber filled with the metal indium at the different temperatures (The dashed line indicates the guide to show the wavelength shift.) and (b) wavelength shift of the fringe with the temperature in the SLI (The solid line represents the linear fit for the wavelength shift.).](image)
4(b). In the SLI with the metal, the wavelength shift sensitivity, $d\lambda/dT = -6.3\ \text{nm/K}$, was one order increased in comparing with the case without the metal and was 3-6 times larger than those of the SLIs based on the highly sensitive birefringent fibers (Fibercore; HB1000, ThorLabs; PM-1550-HP) [4,6,7]. The large wavelength shift sensitivity was explained by the large decrease in the fiber birefringence induced by thermal expansion of the metal during the elevation of the temperature. In the repeated measurement to check the reliability, the variation of the wavelength shift was smaller than 5% in the range of 27-115 °C. Using the resolution (0.01 nm) of the OSA and the sensitivity (−6.3 nm/K), the maximum resolution in the temperature sensing was estimated to be 0.0016 °C. Using Eqs. (5), (6) and the measured wavelength shift sensitivity, the phase change sensitivities ($1/L \cdot d\phi/dT$) were calculated to be $-15.85$ and $-0.249$ rad/K/m in the fiber with and without the metal, respectively.

The temperature sensitivity of the fiber birefringence with and without the metal indium was also investigated from the measured fringe spacing in the temperature range, 27-115 °C. The birefringence of the fiber was calculated using Eqs. (3) and (4) and the results are shown in Fig. 5. In the fiber without the metal, the birefringence was $9.09 \times 10^{-5}$ at 26.7 °C and became slightly decrease to $8.62 \times 10^{-5}$ at 112.2 °C. Whereas the decrement was very strong in the fiber with the metal, the birefringence changed from $3.99 \times 10^{-5}$ to $1.25 \times 10^{-4}$ during the temperature change from 27.0 to 111.3 °C. From the slopes shown in Fig. 5, the temperature sensitivities of the birefringence, $dB/dT$, were obtained to be $-5.36 \times 10^{-8}$ and $-3.32 \times 10^{-6}$/K in the fibers without and with the metal, respectively. The temperature sensitivity was more than 60 times enhanced by incorporation of the metal and it was 4 times larger than that, $-7.5 \times 10^{-7}$/K, of the most sensitive birefringent fiber reported up to now [4].

5. Conclusion

The large temperature sensitivity of the Sagnac loop interferometer based on the birefringent holey fiber filled with metal indium was experimentally demonstrated. For the investigation, an optical fiber with twin hole at both sides of the fiber core was fabricated by the MCVD, mechanical drilling, and fiber drawing processes. The indium inside the holes of the fiber was introduced by injection of the metal at the molten state. The large temperature sensitivity of the fiber was explained by introduction of the additional fiber birefringence originated from the large thermal expansion of indium at the elevated temperature.

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