

Effect of filler metals on the temperature sensitivity of side-hole fiber

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Abstract: Effect of filler metals (Bi, 80Au-20Sn alloy, Sn, and In) on the temperature sensitivity of a birefringent side-hole fiber was investigated. The temperature sensitivity of the fiber was found to increase by introduction of the filler metals and the sensitivity gradually increased with the increase of the thermal expansion coefficient of metals. The sensitivity was larger for the filler metals with the larger thermal expansion coefficient.

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1. Introduction

Different types of birefringent fibers have been developed with the cross-sectional structures of the PANDA, the bow-tie, the elliptical core, and the internal elliptical cladding [1]. Birefringent fibers are used as a polarization maintaining element in optical communication systems and a non-reciprocal optical element in Sagnac loop interferometers for optical filter and sensor applications. Thermal properties of the birefringent fibers have been extensively studied because temperature sensitivity is critical in the optical device applications [2-8]. In the communication system, small temperature sensitivity is required for the stable operation, while large temperature sensitivity is desired in the temperature sensing applications.

Optical fibers with two holes filled with metal have received great interest because they have much potential on the applications of optical communication and sensing devices with the all-fiber feature [9-15]. All-fiber electro-optic interferometers made by side-hole fibers filled with metal were demonstrated for the implementations of modulation [10,11], switching [12], tuning, and short pulse generation devices [13]. The possibility of the fibers on electro-optical polarization control was also demonstrated [14,15]. In the electro-optic applications, metal infiltrated into the holes was used as a conducting electrode to apply voltage during electro-optic operation of the devices.

Recently, we have reported a new class of birefringent optical fibers which has an elliptical core and two holes on both sides of the core [5]. The temperature sensitivity of the fiber could be strongly increased by introduction of metal indium with the large thermal expansion coefficient inside the holes. The fiber filled with indium exhibited 10 times larger wavelength shift sensitivity, $d\lambda/dT = -6.3 \text{ nm/K}$, and 60 times larger temperature sensitivity of the birefringence, $dB/dT = -3.3 \times 10^{-6} \text{ nm/K}$, than those of the fiber without the metal.

For sensing and electro-optic device applications of the side-hole fibers with metals, understanding the effect of filler metals on the optical, electrical, mechanical, and thermal characteristics of the fibers is very important. Various metals such as bismuth-tin alloy [9,15], aluminum [10], gold-tin alloy [12-15], and indium [5], have been tested as electrodes or stress inducing materials and their mechanical properties and electrical stabilities of the metals have been verified. However, effect of filler metals on the thermal property of the fibers has not been fully understood. In this work, therefore, we investigated effect of filler metals on the temperature sensitivity of the birefringent side-hole fiber by using a Sagnac loop interferometry. The side-hole fibers filled with various metals such as bismuth, gold-tin alloy, tin, and indium, with the different thermal expansion coefficients were fabricated. The temperature sensitivity of the fibers was found to increase by the filler metals and the extent of the increase strongly depended on the thermal expansion coefficient of the metals.

2. Fabrication of the birefringent side-hole fibers filled with metals

A birefringent optical fiber was fabricated by the conventional modified vapor deposition (MCVD), the mechanical drilling, and the fiber drawing processes. The fiber was comprised of a germanium doped elliptical core between side holes. The details of the fabrication procedure and the specification of the fiber were described in Ref. 5. The diameters of the fiber and holes were 125 and $\sim 20 \mu\text{m}$, respectively. Several metals such as bismuth (Bi), gold-tin alloy (80Au-20Sn alloy), tin (Sn), and indium (In) were used to investigate effect of filler metals on the temperature sensitivity of the fiber. The molten filler metals at $\sim 25^\circ\text{C}$ higher than their melting temperatures were injected into the holes of the fiber by the aid of nitrogen gas at the pressure of 25 bar and were slowly cool down to room temperature [5].

Fig. 1 shows the SEM images of the fiber end-faces with the holes filled with the different metals. The metals were well incorporated by fully filling the holes of the fibers. Interestingly, the cut shape of the filler metals was different from each other and this may be due to the different mechanical properties of the metals.

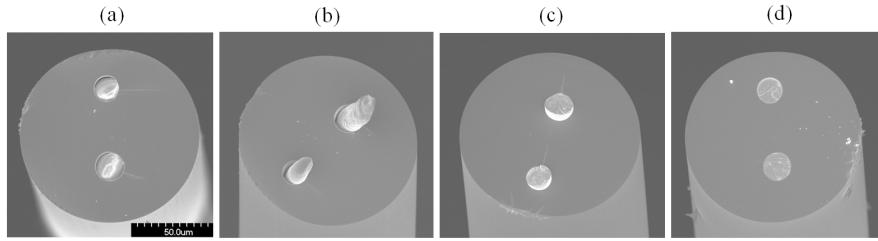


Fig. 1. SEM images of the cut end-faces of the birefringent side-hole fibers filled with the different filler metals (a) In, (b) Sn, (c) 80Au-20Sn alloy, and (d) Bi, respectively.

3. Measurement of temperature sensitivity of the side-hole fiber filled with metals

In order to investigate the temperature sensitivity of the side-hole fibers with metals, the transmission characteristics of the Sagnac loop interferometers (SLIs) made by using the fibers were examined. The schematic setup of the SLI based on the side-hole fiber filled with metal is shown in Fig. 2(a). The fiber loop was composed of the 3 dB optical fiber coupler made by the conventional single mode fiber, the 100 cm-long side-hole fiber which was fusion spliced to the arm of the fiber coupler, and a polarization controller. The length of the metal filled inside the side-hole fiber was 20 cm(L_m) and the other 40 cm(L_n+L_o)-long parts of the fiber at both sides were unfilled regions. Each fiber with the central part of the fiber filled with 20 cm-long metal and 30 cm(L_n)-long side parts without the metal was heat treated inside the heating chamber. Broad-band light (ThorLabs, SOA240) was injected into the input port of the SLI and the transmission spectra at the output port was measured by an optical spectrum analyzer (ANDO, AQ 6317B). Then, the change in the transmission characteristics of the SLI was examined at the different chamber temperatures in the range of 25.4 to 83.4 °C. The experimental conditions such as the total length of the side-hole fiber, the length of the metal inside the fiber, and the heating region, and the temperature range were the same for all of the fibers with different metals.

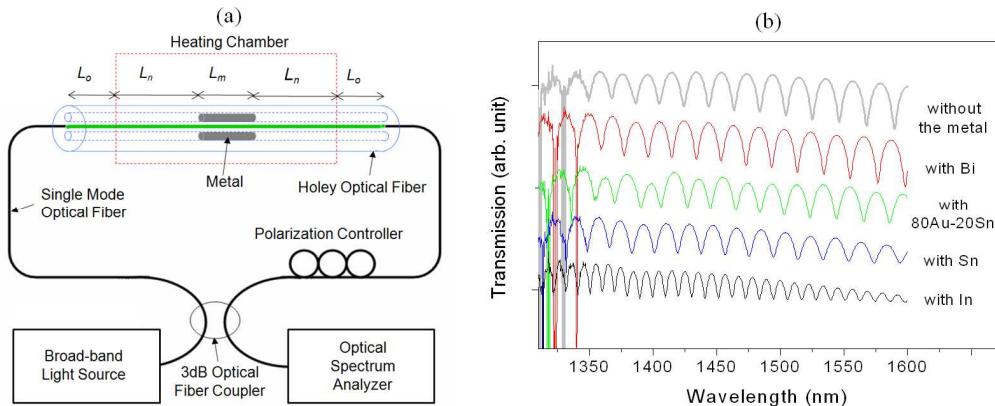


Fig. 2. (a) Schematic setup to measure the temperature sensitivity of the birefringent side-hole fiber filled with the filler metals. (Lengths of each sections of the fiber: $L_m=20$ cm, $L_n=30$ cm, $L_o=10$ cm) and (b) optical transmission spectra of the SLIs based on the side-hole fibers without and with the various filler metals at 25.4 °C.

4. Temperature sensitivity of the side-hole fiber induced by filler metals

Figure 2(b) shows the measured transmission spectra of the SLIs based on the side-hole fibers with different metals at 25.4 °C. The fringe spacing in the reference side-hole fiber without the metals was 19.60 nm. It was found that the fringe spacing of the interference decreased by the incorporation of the metals inside the holes of the fiber. The decrease of the fringe spacing

was larger for the fiber filled with metals having the larger thermal expansion coefficient. The fringe spacings were 18.22, 18.12, 18.07, and 11.69 nm in the SLIs with Bi, 80Au-20Sn alloy, Sn, and In, respectively. The decrease in the fringe spacing can be explained by the increase of the birefringence resulted from the large thermal expansion of the metals [5].

We investigated the birefringence of the side-hole fiber with and without metal at the wavelength of 1340 nm. The birefringence of the side-hole fiber without metal was calculated from the fringe spacing shown in Fig. 2(b) and the equation [16], $B = \lambda^2/(L\Delta\lambda)$, where λ is the operation wavelength, L is the length of the side-hole fiber, and $\Delta\lambda$ is the fringe spacing. The birefringence of the side-hole fiber without metal was calculated to be 9.16×10^{-5} from the fringe spacing of 19.60 nm at 1340 nm. On the other hand, the birefringence was found to slightly increase to be 1.26×10^{-4} and 1.29×10^{-4} when the side-hole fibers were filled with Bi and 80Au-20Sn alloy, respectively. In the case of the metals with the larger thermal expansion coefficient, the more the fiber birefringence increased. The birefringence was 1.30×10^{-4} and 4.02×10^{-4} in the side-hole fibers with Sn and In, respectively. Note that the birefringence of the fiber with metal was calculated by subtracting the contribution ($L_n/L_m B_n + L_o/L_m B_o$) of the fiber region without metal from the total birefringence term ($L_n/L_m B = L_n/L_m \lambda^2/(L\Delta\lambda)$) in Eq. (3) of Ref. 5, where B_n and B_o are the birefringence of the fiber region without metal inside and outside the heating chamber, respectively. Since B_o was equal to B_n at room temperature ~ 25.4 °C, the birefringence of the fiber region with metal was obtained from the equation, $B_m = (L/L_m)B - (L_n/L_m)B_n - (L_o/L_m)B_o = 5\lambda^2/(L\Delta\lambda) - 4B_n$.

The wavelength shift of the interference fringe in the SLI using the side-hole fiber filled with 80Au-20Sn alloy was examined during the temperature change from 28.4 to 83.4 °C. Fig. 3(a) compares the wavelength shift with the temperature in the SLIs using the fiber with and without 80Au-20Sn alloy, respectively. In the both cases with and without 80Au-20Sn alloy, the interference fringe was shifted to the shorter wavelength with temperature increase. In the fiber without metal, the amount of the wavelength shift was 28 nm during the temperature increase from 29.5 to 83.4 °C, while the corresponding wavelength shift in the fiber filled with 80Au-20Sn alloy was 69 nm. From linear fitting of the wavelength shift with temperature, the wavelength shift sensitivity of the SLI with and without 80Au-20Sn alloy was estimated to be -1.35 and -0.62 nm/K, respectively. Interestingly, as shown in Fig. 3(a), the slight longer wavelength shift reported in the previous studies [2,5,6] was also found below ~ 29.5 °C.

The shorter wavelength shift was also found in SLIs using the fibers filled with the other metals (Bi, Sn, and In). The fiber birefringence decreased with the increase of temperature due to thermal expansion of the stress inducing metals inside the holes, resulting in wavelength shift to the shorter wavelength as found in the reports with various birefringence fibers [2,5-8].

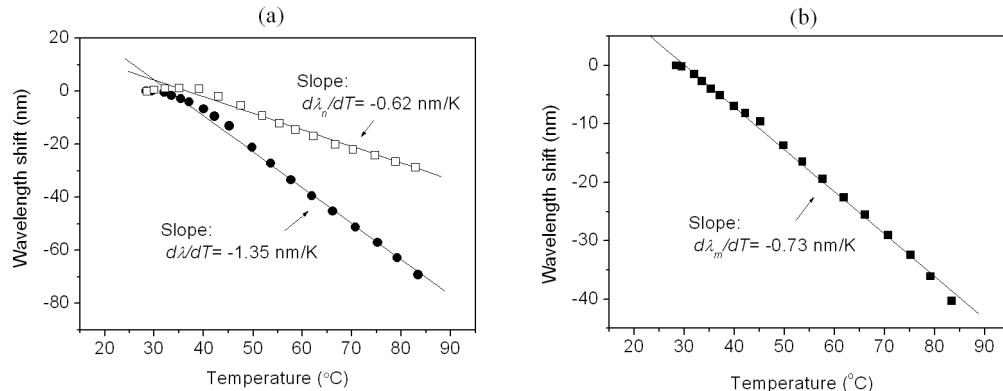


Fig. 3. (a) Wavelength shift of the interference fringe with temperature from 28.4 to 83.4 °C in the SLI based on the fiber filled with 80Au-20Sn alloy and (b) wavelength shift of the fringe induced solely by 80Au-20Sn alloy. (The solid line represents linear fitting of the wavelength shift in the range from 29.5 °C to 83.4 °C.)

To clarify effect of filler metal on the thermal property of the side-hole fiber, the wavelength shift sensitivity ($d\lambda_m/dT$) induced solely by metal was investigated. The wavelength shift sensitivity solely due to metal was obtained by subtracting the wavelength shift sensitivity ($d\lambda_0/dT$) of the fiber without metal from that of the fiber with metal and was expressed as $d\lambda_m/dT = d\lambda/dT - d\lambda_0/dT$, where λ and λ_0 are the wavelength shifts of interference fringe measured from the side-hole fiber with and without metal, respectively. Using the equation and the measured results shown in Fig. 3(a), the wavelength shift solely induced by the metal (80Au-20Sn alloy) was estimated and the result is represented in Fig. 3(b). The wavelength shift was very linear with temperature in comparing with the curved shift shown in Fig. 3(a). The wavelength shift sensitivity, $d\lambda_m/dT = -0.73 \text{ nm/K}$, was identified to be induced solely by the thermal expansion property of 80Au-20Sn alloy. The wavelength shift sensitivities induced solely by the other metals were -0.19 , -2.96 , and -6.01 nm/K in the SLIs using the fibers filled with Bi, Sn, and In, respectively.

From the measured wavelength shift of the SLI with metal, the phase shift induced solely by metal was also estimated using the equation [7,8], $\phi_m = 2\pi B_m L_m / \lambda_m = 2\pi \lambda_m / \Delta\lambda$, where B_m is the metal induced fiber birefringence, L_m is the length of filler metal, and $\Delta\lambda$ is the fringe spacing of the interference. Fig. 4 shows the metal induced phase shift with the increase of temperature. The phase shift with temperature was relatively small in the case with Bi and 80Au-20Sn alloy with the small thermal expansion coefficients (Bi, $\alpha = 13.2 \times 10^{-6} / \text{K}$; 80Au-20Sn alloy, $\alpha = 15.9 \times 10^{-6} / \text{K}$) [17,18]. In the case of Sn and In with the large thermal expansion coefficients (Sn, $\alpha = 22.0 \times 10^{-6} / \text{K}$; In, $\alpha = 32.1 \times 10^{-6} / \text{K}$) [17], on the other hand, the phase shift was strongly increased with temperature. The rate of the phase shift with temperature, $d\phi_m/dT$, were -0.071 , -0.248 , -1.06 , and -3.11 rad/K in the side-hole fibers with Bi, 80Au-20Sn alloy, Sn, and In, respectively. In all fibers, as shown in Fig. 4, the metal induced phase shift was very linear with temperature and this linearity is another advantage for temperature sensing application of the fibers.

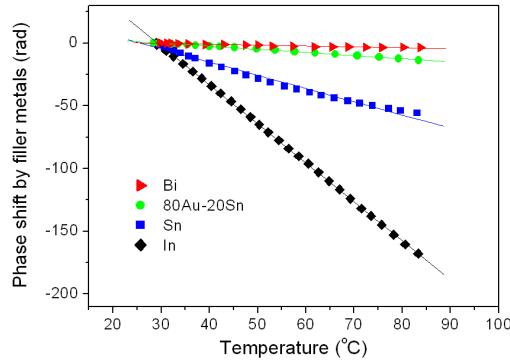


Fig. 4. Phase shift solely due to the filler metals of the side-hole fibers with temperature. Solid lines represent linear fitting.

From the slopes shown in Fig. 4, the metal induced phase shift sensitivity defined by $(1/L_m)d\phi_m/dT$ was calculated and the result was summarized in Table 1. The phase shift sensitivity was -0.35 and -1.24 rad/K/m for Bi and 80Au-20Sn alloy, respectively. For Sn and In with the larger thermal expansion coefficients, the sensitivity was strongly increased to be -5.28 and -15.5 rad/K/m , respectively. The metal induced temperature sensitivity of birefringence given by [2,6] $dB_m/dT = \lambda/(2\pi L_m)d\phi_m/dT$ was also estimated from the phase shift sensitivity and the result was given in Table 1 and Fig. 5. The temperature sensitivity of birefringence induced by metal gradually increased with the increase of the thermal expansion coefficient of metal filled inside the holes of the fiber. Based on the result, however, dependence of the temperature sensitivity on the thermal expansion coefficient of metal was

not linear and further investigation should be followed to fully understand. If the temperature sensitivity of the side-hole fiber filled with metal is considered, the metals such as In and Sn with the large thermal expansion coefficient are candidate materials for sensing applications whereas the metals (Bi and 80Au-20Sn alloy) with the small thermal expansion coefficient are more compatible material for electro-optic application requiring the high thermal stability.

Table 1. Phase shift sensitivity and temperature sensitivity of birefringence induced by the filler metal of the side-hole fiber.

Type of the filler metals	Thermal expansion coefficient, α (/K)	Phase shift sensitivity, $I/L_m d\phi_m/dT$ (rad/K/m)	Temperature sensitivity of birefringence, dB_m/dT (/K)
Bi	13.2×10^{-6}	-0.35	-7.46×10^{-8}
80Au-20Sn alloy	15.9×10^{-6}	-1.24	-2.64×10^{-7}
Sn	22.0×10^{-6}	-5.28	-1.13×10^{-6}
In	32.1×10^{-6}	-15.5	-3.31×10^{-6}

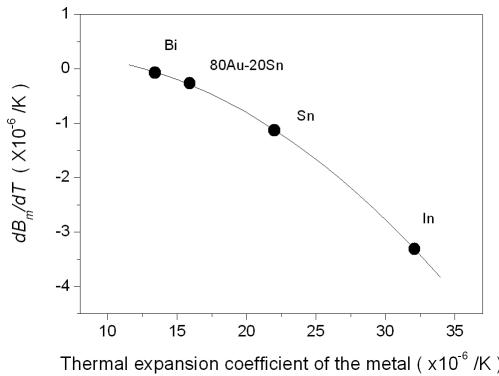


Fig. 5. Metal induced temperature sensitivity of birefringence of the side-hole fibers filled with metals with the various thermal expansion coefficients. The solid line indicates the polynomial fit curve.

5. Conclusion

We investigated effect of filler metals on the temperature sensitivity of the birefringent side-hole fibers using a Sagnac loop interferometer. The side-hole fibers filled with the various metals such as Bi, 80Au-20Sn alloy, Sn, and In with the different thermal expansion coefficients were made by injection of the molten metals. The temperature sensitivity of the fiber was found to strongly increase by introduction of the filler metals. The wavelength shift sensitivities were -0.19 and -1.35 nm/K of the fibers filled with Bi and 80Au-20Sn alloy, respectively. The sensitivity increase was much stronger in the case of the metals (Sn, -2.96 nm/K; In, -6.01 nm/K) with the larger thermal expansion coefficients. The metal induced sensitivity was also found to show the very linear characteristics upon temperature change.

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