Effect of infiltration pressure on the birefringent properties of a side-hole fiber filled with indium

Seung Ho Lee,1 Dong Hoon Son,1 Bok Hyeon Kim,2,4 and Won-Taek Han1,3,*

1Department of Photonics and Applied Physics, Gwangju Institute of Science and Technology (GIST), 1 Oryong-dong, Buk-gu, Gwangju 500-712, South Korea
2Advanced Photonics Research Institute (APRI), GIST, 1 Oryong-dong, Buk-gu, Gwangju 500-712, South Korea
3School of Information and Communications, GIST, 1 Oryong-dong, Buk-gu, Gwangju 500-712, South Korea
4e-mail: bhkim@gist.ac.kr

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The effect of the infiltration pressure on the birefringent properties of a side-hole fiber filled with indium was investigated by the fiber-optic Sagnac loop interferometry. The fiber was made at the various gas pressures during the infiltration process. It was found that the birefringence of the fiber strongly decreased from $5.55 \times 10^{-4}$ to $1.68 \times 10^{-4}$ with the increase of the pressure from 15 to 45 bars, due to the compensation effect of the pressure applied during the infiltration. The temperature dependence of the birefringence, $dB_n/dT$, was found to be constant of $\sim -3.06 \times 10^{-4}/K$ regardless of the magnitude of the pressure. © 2012 Optical Society of America

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Optical fibers containing longitudinal side-holes filled with various materials, such as metal, polymer, semiconductor, and chalcogenide glass, have received much attention because of their potentials for fiber-optic device applications [1–7]. Recently, we have reported a new class of side-hole glass fiber that has an elliptical core and side-holes filled with indium metal by using the infiltration method [8–10]. The infiltration process was performed by pushing the metal in the molten state into the holes with the aid of nitrogen gas. The advantages of the process made it possible to continuously integrate the indium in the long length and completely fill the cross section of the holes in the glass fiber with indium. Indium was used as a stress-inducing material in the fiber because of its very large thermal expansion coefficient and the possibility of temperature sensor applications. The birefringence increased more than four times, and the temperature sensitivity of the birefringence was enhanced 60 times by the incorporation of indium [8,9].

Although large temperature sensitivity is desirable for sensing applications, the small sensitivity is required for the stable operation in other electro-optic devices. For reliable fiber-optic devices, therefore, it is essential to understand the effect of metal infiltration conditions on the properties of the fiber. Up to now, optical fibers integrated with various metals [11,12] and alloys [2,3,10] were introduced and their optical, thermal, and mechanical properties, and their electrical stabilities have been investigated for electro-optic and sensing applications. In the previous study, we investigated the effect of filler metals with different thermal expansion coefficients on the birefringence of the fibers [9]. The effect of the infiltration conditions, as well as the metals themselves, on the optical properties (especially for the birefringent properties of the fibers) has not been fully understood.

In this study, we made side-hole glass fibers filled with indium metal by the infiltration method, and various gas pressures were applied during the infiltration. The effect of the infiltration pressure on the birefringence and its temperature sensitivity in the fibers were investigated. It was found that the birefringent properties were strongly affected by the infiltration condition.

A glass fiber preform made by the modified chemical vapor deposition (MCVD) process was mechanically drilled to make two side-holes adjacent to a germanium-doped core and was drawn into an optical fiber with the diameter of 125 μm. The side-holes were slightly collapsed to make an elliptical core during the fiber drawing process. The hole diameter was ~17 μm and the refractive index difference between the core and the cladding was ~0.0018. Using the infiltration technique [8–10], molten indium at 180 °C was filled into the side-holes by the aid of nitrogen gas at the various gas pressures, 15–45 bars, and cooled down to room temperature maintaining the designated pressures. Figures 1(a) and 1(b) show the scanning electron micrographs (SEM) of the fiber filled with and without indium. As shown in the figure, indium metal was completely filled inside the side-holes of the fiber without air gaps. Note that...
asymmetry in the radial position and the size of the holes was also found, and this may be due to the incomplete machining of the holes during the drilling process.

The birefringence of the side-hole fiber with and without indium and the temperature dependence of the birefringence were estimated by measuring the transmission characteristics of the fiber-optic Sagnac loop interferometer (SLI). The detailed operation principle of the SLI has been described in previous studies [8,13]. An optical fiber coupler in the SLI equally splits the input optical signal into two counter propagating waves. Subsequently the waves recombine, resulting in interference patterns after passing through the same length of the fiber loop because of the phase difference in the two principle propagating modes of the birefringent fiber. The transmission of the SLI is given by the periodic function, \( T = [1 - \cos(\varphi)]/2 \), where the phase difference \( \varphi = 2\pi BL/\lambda \) and \( B \), \( L \), and \( \lambda \) are the fiber birefringence, the length of the birefringent fiber, and the wavelength, respectively. The schematic diagram of the SLI made by a 100 cm long side-hole fiber filled with indium is shown in Fig. 1(c). The 20 cm long center region of the fiber was filled with indium, and the other side regions of the fiber were retained unfilled to fusion splice with a conventional single-mode fiber (SMF). After launching the light from a broadband source (ThorLabs, SOA 240) into the input port and maximizing the interference contrast using a polarization controller (PC), the transmission spectra of the SLI were measured by an optical spectrum analyzer (ANDO, AQ 6317B) at different temperatures from 18.5 °C to 121.3 °C. Then the temperature dependence of the birefringence of the fiber with indium was examined from the measured optical spectra. As a reference, the transmission characteristics of the SLI made by a 100 cm long side-hole fiber without indium were also investigated.

Figure 2 compares the transmission spectra of the SLIs made by the side-hole fiber with and without indium at the various infiltration pressures of 15–45 bars and the fixed temperature of 18.5 °C. In the fiber without indium, the extinction ratio of \( \sim 10 \) dB was obtained and the interference fringe spacing was 20.34 nm near the wavelength of 1550 nm. From the fringe spacing (\( \Delta \lambda \)), the birefringence (\( B_n \)) of the fiber without indium was obtained to be \( 1.18 \times 10^{-4} \) using the equation \( B_n = \lambda^2/(L\Delta \lambda) \) [13].

In the case of the fiber filled with indium, the interference fringe spacing was smaller than that of the fiber without indium as shown in Fig. 3. The fringe spacing gradually increased from 11.67 to 18.69 nm with the increase of the infiltration pressure. Indium was well adhered to the inner surface of the side-holes of the silica fiber [14] and shrunk much more than the fiber material because of its very large thermal expansion coefficient (\( \alpha = 32.1 \times 10^{-6} \) K\(^{-1} \)) [15], resulting in the buildup of tensile stress and the increase of fiber birefringence. The birefringence of the fiber with indium, \( B_m \), was obtained from the fringe spacing and the birefringence of the fiber without indium using the equation, \( B_m = (L/L_m)[\lambda^2/(L\Delta \lambda)] - (L_m/L_m)B_n = 5[\lambda^2/(L\Delta \lambda)] - 4B_n \) [9], where \( L \) (100 cm), \( L_m \) (20 cm), and \( L_6 \) (80 cm) are the lengths of the total side-hole fiber, the fiber region with indium, and the fiber region without indium, respectively. The birefringence of the fiber with indium at 15 bars was \( 5.55 \times 10^{-4} \) (this was much larger than that of the fiber without indium) and considerably decreased to \( 1.68 \times 10^{-4} \) as the pressure increased to 45 bars, as shown in Fig. 3. The birefringence solely induced by indium in the fibers was estimated from \( B_i = B_m - B_n = 5[\lambda^2/(L\Delta \lambda)] - 5B_n \) and the results were also given in the figure. The birefringence was \( 4.37 \times 10^{-4} \) at 15 bars, whereas the comparatively small birefringence of \( 5.00 \times 10^{-5} \) was obtained at 45 bars.

The birefringence could be varied in a side-hole fiber by applying gas pressures to the internal and external sides of the air holes, and the variation was explained by the stress induced from the pressure [16]. On the basis of the similar consideration, the variation of the birefringence with the increase of the infiltration pressure can be explained by the compensation effect of the tensile stress from the thermal expansion of indium (positive effect to the birefringence) by the compressive stress from the pressure (negative effect to the birefringence). When a low pressure is applied during infiltration and solidification of indium, the holes are slightly expanded by the pressure, and this builds up the small compressive stress in the fiber core and makes the birefringence decrease. The negative effect by the pressure is much smaller than the birefringence increase from the metal shrinkage, however, and thus the total increase amount in the birefringence is very large. If a high pressure is applied,
on the other hand, the compressive stress applied to the core becomes much larger, and most of the tensile stress from the thermal expansion of indium is compensated. Therefore, the increase amount of the birefringence was much smaller than the case with the low pressure. From the result, we can expect that the birefringence can be controlled by varying the pressure during the metal infiltration process in the fiber for proper applications.

To clarify the thermal property of the side-hole glass fiber, we investigated the fiber birefringence at the different temperatures by monitoring the transmission spectra of the SLIs. Figure 4 shows the temperature dependence of the birefringence of the fibers filled with indium at the different infiltration pressures. In the case of low pressure of 15 bars, the birefringence linearly decreased from 5.55 × 10⁻⁴ to 2.52 × 10⁻⁴ during the whole temperature range from 18.5 °C to 120.7 °C. In the pressure of 35 bars, the birefringence also linearly decreased from 2.21 × 10⁻⁴ to 1.10 × 10⁻⁴ in the temperatures from 18.5 °C to 54.5 °C, however, the decrease became nonlinear from 60 °C, then interestingly saturated to the value of ~8.04 × 10⁻⁵ without further decrease. The birefringence from 54.5 °C became smaller than that of the fiber without indium at 18.5 °C. Similar trends were also found in other high pressures, such as 30 and 45 bars. The decrease in the birefringence was linear in low temperatures and became saturated to the similar value of ~8.10 × 10⁻⁵ from the temperatures of 60 °C to 80 °C. We carefully guess that this unusual saturation can result from the anomalous birefringent property of the fiber that cooled down under the high stress [17] or from the limitation in the thermal expansion of indium restricted by the rigid fiber material at a certain boundary state. The temperature sensitivities of the birefringence were derived by fitting the linear regions in low temperatures. Regardless of the infiltration pressures, the similar sensitivity of $dB_m/dT = \sim 3.06 \times 10^{-6}/K$ was obtained. The possible explanation for this consistency is that the thermal expansion property of indium is constant and may not be strongly influenced by the applied pressure.

In conclusion, we made the side-hole fibers filled with indium at the various infiltration pressures, 15–45 bars, and the effect of the infiltration pressure on the birefringent properties of the fibers were investigated using the fiber-optic SLI. It was found that the birefringence of the fiber was strongly affected by the infiltration pressure. As the pressure increased, the fiber birefringence considerably decreased from 5.55 × 10⁻⁴ to 1.68 × 10⁻⁴. The decrease of the birefringence was explained by the compensation of the tensile stress from the thermal expansion of indium by the compressive stress built up from the infiltration pressure. The temperature sensitivity of the birefringence in the linear region was almost constant of $dB_m/dT = \sim 3.06 \times 10^{-6}/K$ regardless of the infiltration pressure; on the other hand, the birefringence showed anomalous property and saturated to the constant value of ~8.10 × 10⁻⁵ in the fibers with the high infiltration pressures.

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