DOI: 10.1063/1.4902157

Temperature sensibility of the birefringence properties in side-hole photonic crystal fiber filled with Indium

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(Received 29 August 2014; accepted 8 November 2014; published online 17 November 2014)

We report on the temperature sensitivity of the birefringence properties of a special kind of photonic crystal fiber containing two side holes filled with Indium metal. The modulation of the fiber birefringence is accomplished through the stress field induced by the expansion of the metal. Although the fiber was made at low gas pressures during the indium infiltration process, the birefringence showed anomalous property at a relatively low temperature value, which is completely different from those reported in conventional-like fibers with two holes filled with metal. By modeling the anisotropic changes induced by the metal expansion to the refractive index within the fiber, we are able to reproduce the experimental results. Our results have practical relevance for the design of devices based on this technology.
[http://dx.doi.org/10.1063/1.4902157]

Optical fibers with side holes filled with metal are a promising technology to actively control light inside a fiber. These devices are potentially cheap and provide simple, low loss, and robust integration with other fiber components through splicing.[1] Conventional-like fibers with two holes filled with metal were demonstrated to create a large and stable second-order optical nonlinearity through thermal poling by using the metal filled holes as internal electrodes for applying a high electric field across the fiber core.[2–4] Such second-order nonlinearity in optical fibers has been used in a wide range of applications such as electro-optic modulation and switching.[5,6] Recently, ohmic heating of the metal filled holes has also shown to be an effective means of controlling the optical properties of the fiber, leading to the development of thermal devices based on polarization control and wavelength switching.[1]

Photonic crystal fibers (PCFs), also called holey fibers, offer interesting possibilities for tailoring the transmission properties of optical signals through optical fiber.[7] Extra flexibility is gained by filling the open channels of the fiber by substances whose optical properties can be externally controlled.[8–10] The active control of PCF-based devices as well as the device construction itself can be significantly improved by integrating electrodes into the fiber. In a recent paper, it was proposed a PCF containing two side holes filled with a metal alloy for purposes of electro optic switching by passing a current pulse through one of the metal infiltrated holes.[11] Here, we report on the temperature sensitivity of the birefringence properties of a PCF with the side holes filled with indium metal. The modulation of the fiber birefringence is accomplished through the stress field induced by the expansion of the metal filled holes. As the metal expansion depends linearly on the temperature chance, a larger expansion coefficient is advantageous. Indium was expected to induce a very large thermal stress since the thermal expansion coefficient of the metal ($\alpha = 32.1 \times 10^{-6}\,\mathrm{K}^{-1}$) is at least one order of magnitude larger than that of the fiber material ($\alpha = 0.5 \times 10^{-6}\,\mathrm{K}^{-1}$).[12]

Figure 1(a) shows the cross-section of the fiber used in this study. The silica fiber has an external diameter of approximately 170 μm. The microstructure consists of five rings of air holes with a diameter (d) of 1.05 μm and a 2.6 μm diameter solid core. The average pitch (Λ) is 2.4 μm, so the ratio d/Λ is 0.44. The two side holes have a width of approximately 23 μm and approximately 15 μm separates them from the edges of the core. Molten indium at 200 °C

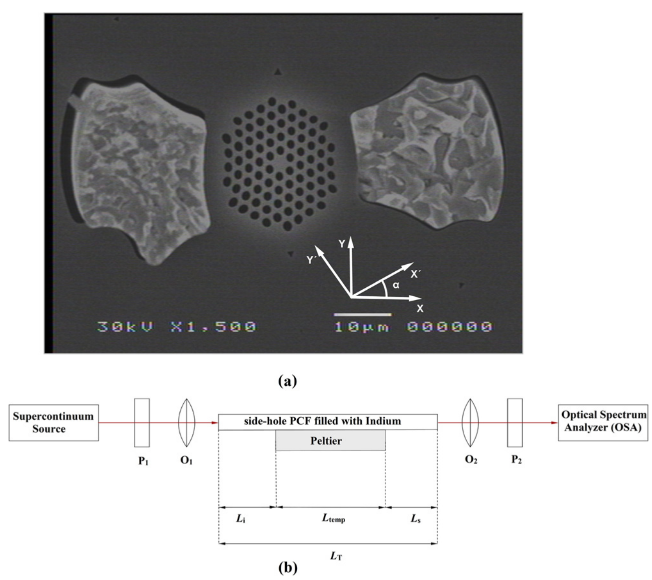

FIG. 1. (a) SEM image of the side-hole PCF. (b) Experimental setup for characterizing the group birefringence properties of side-hole PCF filled with Indium. P1 = P2 = polarizer; O1 = O2 = objective. The structural parameters used in this study are the following: $L_T = 22.25$ cm and $L_{tem} = 8$ cm.

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was injected into the side holes of the fiber by the aid of compressed air at 3 bars, then self-cooling with the chamber turned off and closed.[11] The advantage of the filling procedure is that it provides continuous metal wires that completely fill the cross-section of the holes.

The temperature sensitivity of the group birefringence of the PCF was investigated by using the crossed polarizer low coherence interferometric method. To implement this technique, the interferometer shown in Fig. 1(b) was constructed. Spectral interferences were recorded over a large range of wavelengths by illuminating the fiber under test with a supercontinuum source whilst recording the output spectrum using an optical spectrum analyzer (AQ6319, Yokogawa, Japan). Here, it should be noted that the total length of fiber sample L_T (22.25 cm) and a length L_{tem} (8 cm) was located on the semiconductor Pertier cooler. The fiber was positioned so that both metal-filled holes are at the same distance from the cooler, thus ensuring uniform thermal conditions. The group birefringence in the fiber region exposed to temperature variations can be expressed as

$$G_{temp} = \frac{\lambda^2}{L_{temp}\Delta\lambda} - G_0 \frac{L_0}{L_{temp}}, \quad (1)$$

where $\Delta\lambda$ is the wavelength spacing between neighboring peaks at the central wavelength λ, $L_0 = L_i + L_s$ [see Fig. 1(b)], and G_0 is the group birefringence of the side-hole PCF filled with indium at room temperature.

We investigated the residual birefringence in the fiber induced by the metal filling process. The results are shown in Fig. 2(a) at room temperature (the Peltier cooler is off), ~22 °C. As we can see, the metal filling procedure increases the group birefringence for the entire spectral range, being the largest influence at long wavelengths. For example, the group birefringence increased by 55% at 1550 nm by incorporation of metal. This may be explained by the gradual expansion of the propagation mode into the cladding since the magnitude of the stress field is to be large in the region between air holes than in the core itself.

Figure 2(b) compares the temperature sensitivity of the fiber group birefringence for three representative wavelengths. For short wavelength, $\lambda = 980$ nm, it is observed that the birefringence slightly decreased, stabilizing its value from about 35 °C. For long wavelengths, $\lambda = 1310$ nm and $\lambda = 1550$ nm, the group birefringence decreased considerably at low temperatures (22–45 °C), after which it began to increase. These experimental results demonstrate that the birefringence in the side-hole PCF filled with indium has anomalous property although the fiber was made at low gas pressures during the metal infiltration process. This behavior is quite different from conventional-like fibers with two holes filled with indium which, in the case of low infiltration pressures, the birefringence decreases linearly with the temperature, whereas in the case of high infiltration pressures (>20 bar), the birefringence decreases linearly at low temperatures (18.5–54.5 °C), after which the decrease becomes nonlinear, saturating from 60 °C without further increases.[13]

When heat is transferred to the PCF, the metal expands and squeezes the fiber microstructure. As a result of the photoelastic effect, stress induces anisotropic changes of refractive index within the fiber and thus modifies the residual birefringence in the fiber. We performed finite element simulations (COMSOL Multiphysics) of the side-hole PCF filled with indium under different temperature conditions. In the modeling procedure, we first estimate the stress components and structure deformations generated by the metal infiltration process, resulting from the difference of thermal expansion coefficients of silica and indium. To do so we determined through an iterative process, the residual stress distribution, and structure deformations on the fiber cross section using a plain-strain model,[14] such that for a selected wavelength is possible to reproduce the increase in the group birefringence shown in Fig. 2(a). In a second step, we calculated the spectral dependence of the phase modal birefringence $B(\lambda)$ taking into account both the whole geometry of the PCF and the effect of the thermal stress. The stress-induced changes to the refractive indices were used to solve the full vectorial wave equation for accurate determination of the phase modal birefringence, assuming that the refractive index of silica satisfies the Sellmeier equation.[15] As an example of the above procedure, Fig. 3 shows the calculated distribution of the stress-induced refractive index change along the principal axis at a wavelength of 1550 nm for the

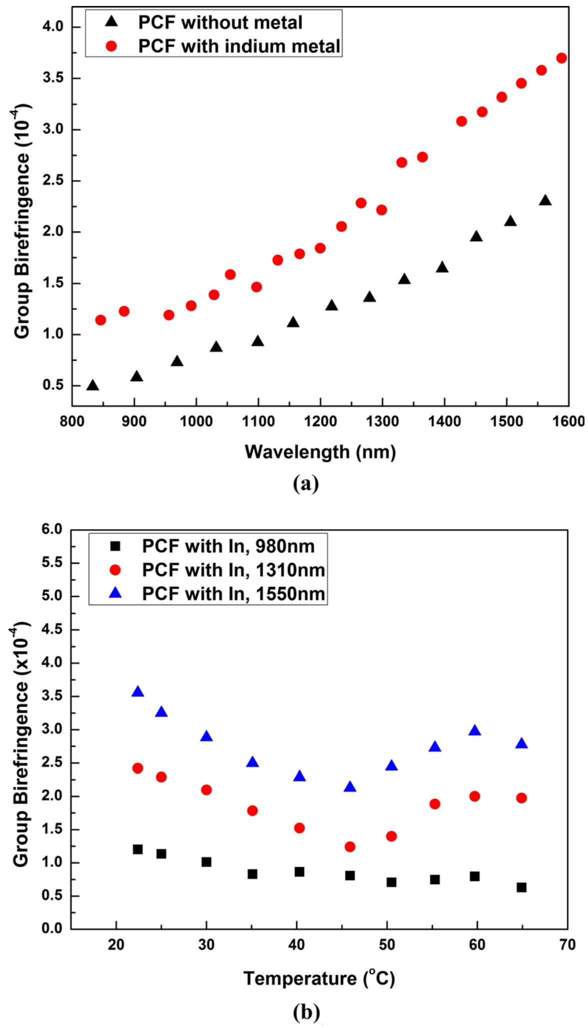

FIG. 2. Characterization of the side-hole PCF. (a) Spectral dependence of the group birefringence with and without indium insertion process at room temperature (22 °C). (b) Group birefringence with side holes filled with indium (In) as a function of temperature for three representative wavelengths.

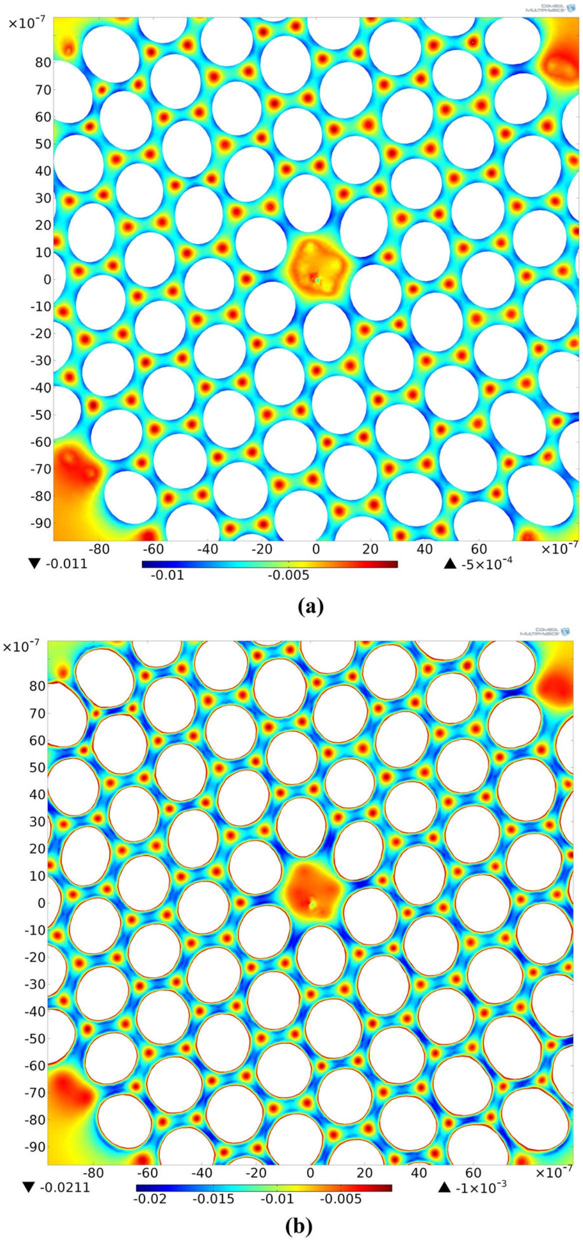

FIG. 3. Calculated distribution of the stress-induced refractive index change along the principal axis at a wavelength of 1550 nm for the microstructure when the temperature changes from 22 °C to 70 °C.

microstructure when the temperature changes from 22 °C to 70 °C. Once the phase modal birefringence at a given temperature was determined for the set of wavelengths, the discrete values of $B(\lambda)$ were numerically approximated with a power law function,[16] which allowed us to easily calculate the group birefringence G through its functional form

$$G = B(\lambda) - \lambda \frac{dB(\lambda)}{d\lambda}. \tag{2}$$

In the calculations of stress components, structure deformations, and anisotropic changes of refractive index, we used material constants and elasto-optic coefficients that were adequate for silica glass and indium metal.[14,17]

The effect of the expansion of the metal with the temperature begins to be observed through the stress field, whose lines are ruled by the distribution of the holes in the microstructure and modify the residual stresses induced by metal infiltration process, modulating the birefringence of the side-hole PCF. As an example, Fig. 4(a) shows the average value of the principal stresses $\sigma_{x'}$ and $\sigma_{y'}$ near the fiber center versus temperature, where it is clear that stresses have opposite behaviors, i.e., $\sigma_{x'}$ ($\sigma_{y'}$) decreases (increases) linearly with temperature. In this figure, we can observe three basic regions, which define the optical response of the side-hole PCF. In region I, $\sigma_{y'}$ is initially a compressive stress (negative stress) which decreases at a rate of 1.2×10^6 Pa/°C and quickly, at T = 32 °C, becomes a tensile stress (positive stress); moreover, in this temperature range, $\sigma_{x'}$ is a tensile stress which decreases at a rate of -1.6×10^6 Pa/°C. This state of the principal stresses causes the group birefringence decreases with temperature as evidenced from the experimental results of Fig. 2(b). Region II is located in the temperature range from 32 °C to 53 °C where both principal stresses are positive and exhibit a crossing point at T = 44 °C. These conditions explain the nonlinear behavior observed in the experimental results of Fig. 2(b), in which G decreases apparently with a different slope from the region I, reaches a minimum value, and then begins to increase with a different slope to the first part of this region. Finally, in the region III, T > 53 °C, $\sigma_{x'}$ is a compressive stress, while $\sigma_{y'}$ is still a tensile stress. This condition results in that the group birefringence increases linearly with temperature as shown

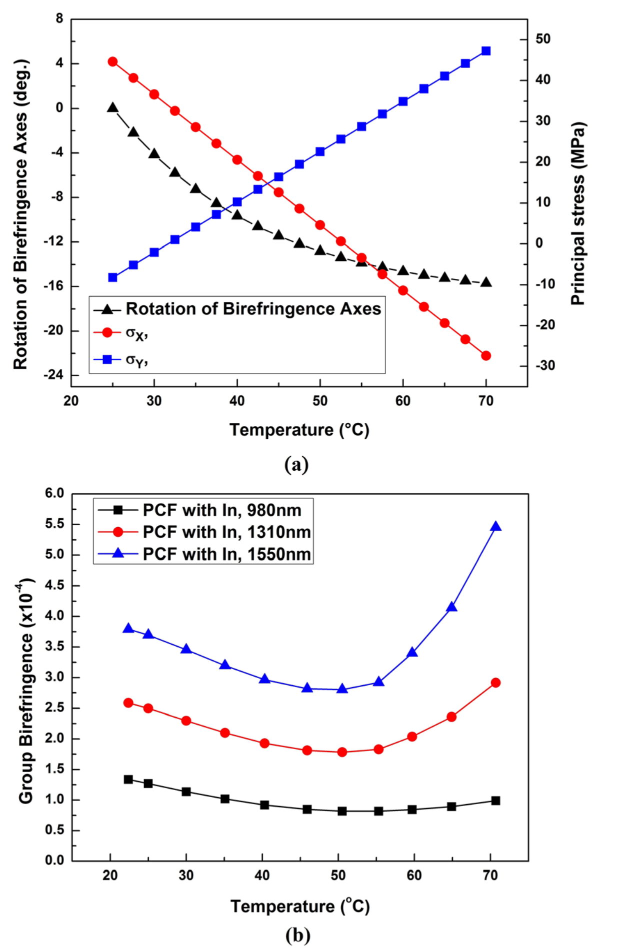

FIG. 4. (a) Calculated average value of principal stresses near the fiber center and rotation of birefringence axes vs. temperature. (b) Calculated group birefringence vs. temperature for three representative wavelengths.

in Fig. 2(b). As noted previously, the confinement factor of the fundamental mode in the holey fibers decreases with wavelength. Therefore, the temperature sensitivity of the birefringence properties the side-hole PCF filled with indium increases with wavelength because of spreading of the mode energy deeper into the cladding.

The simulations also show that the birefringence axes of the PCF rotate as the temperature is increased. As we can see in Fig. 4(a), the birefringence axes initially rotate linearly with temperature, reach a nonlinear regime from $T = 32\,^{\circ}C$, and achieve a maximum rotation angle of 16° at $T = 70\,^{\circ}C$. This rotation of the birefringence axes is the result of the photoelastic effect in the presence of shear stress. Therefore, in this case, one cannot assume that the original optical axes and the birefringence axes of the PCF overlap.

Figure 4(b) shows the simulated group birefringence at three wavelengths of interest versus temperature to reproduce the experimental results plotted in Fig. 2(b). Note that our model describes the anomalous behavior in the group birefringence at long wavelengths; it also accounts for the slight decrease in the group birefringence at short wavelengths. From a comparison between theoretical curves of Fig. 4(b) and experimental curves of Fig. 2(b), it can be observed that the simulations predict that the minimum value in the group birefringence occurs at $T = 50.5\,^{\circ}C$ when the experimental result is around $T = 46\,^{\circ}C$. The differences between theoretical and experimental results are attributed to variations in the diameters of the lateral holes of the fiber. As noted previously, the possibility of having a photonic crystal fiber containing two side holes filled with metal opens several interesting possibilities of playing with the insertion of electrically/temperature sensitive materials for the design of active fiber devices.

In summary, we have reported on the birefringence properties of a special kind of photonic crystal fiber containing two side holes filled with indium metal. The modulation of the fiber birefringence is achieved through the stress field induced by the expansion of the metal filled holes. We demonstrate that the fiber structure and the confinement factor of the fundamental mode significantly influence the temperature sensitivity of the birefringence. The information obtained in this study can be utilized in the design of all-fiber devices based on the dynamic squeeze of the microstructure and its influence over its polarization properties.

This work was supported in part by the Universidad Nacional de Colombia (Project 120201003), in part by the Instituto Tecnológico Metropolitano (Project P14102), and in part by the Brazilian agencies CAPES, FAPESP, and FINEP.

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