Guiding and birefringent properties of a hybrid PDMS/Silica photonic crystal fiber

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ABSTRACT

In this work, we demonstrate a highly birefringent (Hi-Bi) photonic crystal fiber (PCF) infiltrated with PDMS elastomer in order to enhance the sensitivity of the fiber to external temperature variations. Index guiding mechanism of the new PDMS/Silica structure and birefringent properties were investigated numerically and experimentally. We investigated the temperature dependance of birefringence from 20-120°C. For the particular design of Hi-Bi PCF, the cut-off operating wavelength of the hybrid fiber was found to be around 750 nm. We also experimentally demonstrate the effect of the elastomer inclusions to the polarization of the fiber. The sensitivity of the PDMS/Silica Hi-Bi fiber was found to be ~ 0.37 rad/K/cm for temperatures ranging from 20 to 80°C. The total length of the hybrid PCF examined was about 1.4 cm.

Keywords: tunable birefringence, hybrid fiber, all-fiber device, polymer, temperature sensor, photonic crystal fiber

1. INTRODUCTION

Great scientific and technological interest has been drawn over the last decade to a type of optical fiber with very interesting guiding properties: the photonic crystal fiber (PCF)[1]. In contrast to conventional fibers, PCFs are made by using just a single material, for example fused silica, and have a regular pattern of tiny air holes running along their length. Their great advantage is that by varying the size and location of the holes, the fiber mode shape, non-linearity, dispersion and birefringence can reach values that are not achievable in conventional fibers. PCFs can be made highly birefringent[2]: the large index contrast facilitates high form birefringence, and the stack-and-draw fabrication process permits the formation of the required microstructure near the fiber core. Beat lengths as low as 600 μm at a wavelength of 1550 nm have been reported[3]. Infiltration of different materials into the air holes of PCFs can potentially manipulate their optical properties yielding novel hybrid all-fiber optical devices, creating a new category of fibers termed as *hybrid PCFs*[4]. Many hybrid devices such as switches[5], tunable devices[6], sensors[7, 8] have been developed and studied by filling liquid crystal, high index fluids, metals[9] as well as other materials into the air holes by transforming an index guiding PCF into a photonic bandgap fiber (PBG)[10]. However, limited research has been so far carried out on the infiltration of PCF's holes with polymeric inclusions, conserving total internal reflection (TIR) guiding mechanism. In 2002, C. Kerbage *et al.* reported a microstructured optical fiber (MOF) with germanium doped core and six big air holes in the cladding[11]. They demonstrate introduction of birefringence into MOF by selectively infusing polymer into the holes of the MOF. However, it is worth noting that the presented approach required post-processing of the fiber (i.e. tapering), selective filling technique, while the MOF used in their experiments is not commercially available. Recently, C.Markos *et al* reported infiltration of PDMS elastomer into a conventional PCF showing how the thermo-optic effect of the elastomeric inclusions reconstruct the fundamental guiding mode of a bent PCF[12].

PDMS (Poly-dimethylsiloxane) elastomer is a widely used material in the area of photonics and particularly in opto/microfluidics. It owns unique optical properties such as transparency for a wide range of wavelength, lower refractive index (around 1.41) than fused silica, negligible birefringent, minimal loss due to absorption and exhibits very good mechanical properties due to low Young's modulus; it is soft and deformable with no shrinkage and suitable material for molding applications[13]. These properties combined with its low cost, and ease fabrication procedure makes PDMS a potential active material for tunable devices and sensing applications.

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In this work, we report for the first time to our knowledge a combination of the aforementioned polymeric material with a Hi-Bi PCF. We examined the basic guiding and birefringent properties of the PMDS/Silica structure numerically and experimentally. We show that by varying external temperature (20 - 80°C), it is possible to monitor the polarization of the hybrid fiber and estimate the device's sensitivity. It must be noted here that all-silica Hi-Bi PCFs have been found to be almost insensitive within this range of temperatures[14].

2. EXPERIMENTAL

In our experiments, we employed a Hi-Bi PCF with diameter of d_1 = 1.15 μm for small holes, d_2 = 2.15 μm for the large holes arranged in a hexagonal pattern with hole pitch of Λ = 2.23 μm, as shown in Fig. 1(a). The total diameter of the fiber is 125 μm. PDMS (Sylgard 184-Dow Corning) was prepared by mixing elastomer and curing agent at 10:1 ratio. A simple custom-build pressure cell was used to inject the material into PCF's air holes. Figure 2(b) shows the Scanning Electron Microscopy (SEM) image of the hybrid PDMS/Silica PCF indicating that all the holes of the fiber are filled with the elastomeric material. The total length of the hybrid fiber was around L ~ 1.4 cm.

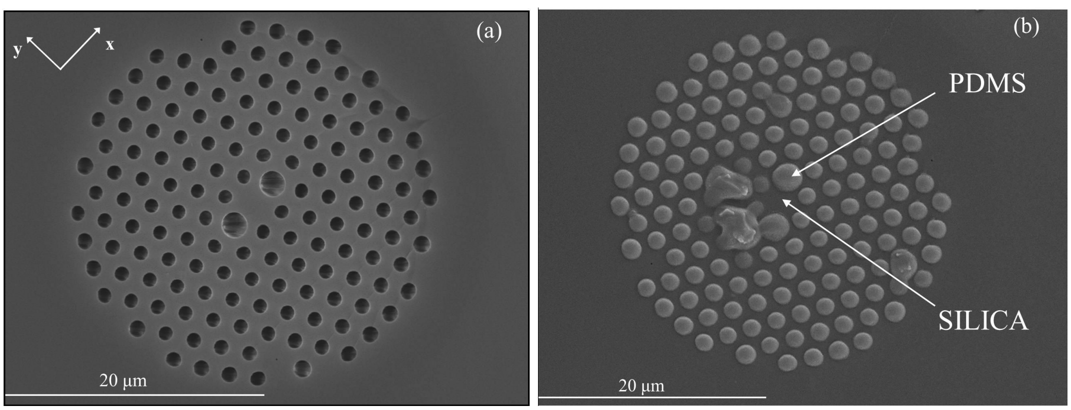

Figure 1 (a) Scanning electron microscopy (SEM) image of a conventional Hi-Bi photonic crystal fiber. (b) SEM image of the hybrid PDMS/Silica photonic crystal fiber.

3. RESULTS AND DISCUSSION

1.1 Simulation

The numerical investigation of both conventional and hybrid Hi-Bi PCF was done by employing the fully vectorial integrated mode solver of the commercially available *Lumerical FDTD solutions* software[15]. The effective index of the fundamental guided mode was computed based on finite difference analysis using Yee's mesh and the index averaging technique utilizing perfectly matched layer (PML) boundary conditions[16] .To calculate the birefringence, in the hybrid PCF, a structure with the same structural parameter as the real fiber was created. It should be mentioned that in this work we refer only to the phase birefringence. Dispersion of both materials (silica and PDMS) was included in our calculations using their Sellmeier equations[17, 18]. The effective indices of both orthogonal polarizations (x and y polarization) of the fundamental mode is then calculated for a range of wavelengths from 400 - 633 nm. The magnitude of the birefringence is obtained by taking the difference between the effective indices of the two different polarizations of the fundamental mode and is defined as:

$$B = \left| n_x^{eff} - n_y^{eff} \right| \quad (1)$$

where n_x^{eff} and n_y^{eff} are the effective indices of both the x and y polarization mode, respectively.

In Fig. 2 (a), we demonstrate the calculated fundamental guiding mode profile of a conventional Hi-Bi PCF same as in Fig. 1(a) at 633 nm wavelength. Infiltration of PDMS elastomer into the holes of the Hi-Bi PCF decrease the mode confinement caused by the lower refractive index difference between Silica and PDMS. Therefore the fundamental modal area has been expanded as can be clearly seen in Fig. 2(b). The absorption loss of PDMS at 633 nm wavelength is very low as has been experimentally demonstrated[18]. Figure 2 (c) demonstrate the birefringence for the conventional Hi-Bi fiber with respect the wavelength at short wavelengths (400-633 nm). Figure 2 (d) show the significant decrease of the birefringence in case of the Hi-Bi PCF with the elastomer inclusions. The beat length can be described in terms of birefringence as: $L_B = \lambda/B$, where B is the birefringence of the fiber. At operating wavelength of 633 nm, the birefringence of the conventional Hi-Bi PCF is ~ $2.32\text{x}10^{-4}$ which gives a beat length of L_B ~ 2.72 mm, while in the hybrid PDMS/Silica PCF, birefringence is around an order of magnitude less, i.e. B ~ $2{,}5\text{x}10^{-5}$, corresponding to a beat length of L_B ~ 2.532 cm. For the particular Hi-Bi fiber design, the cut-off operating wavelength with acceptable loss was found to be around 750nm.

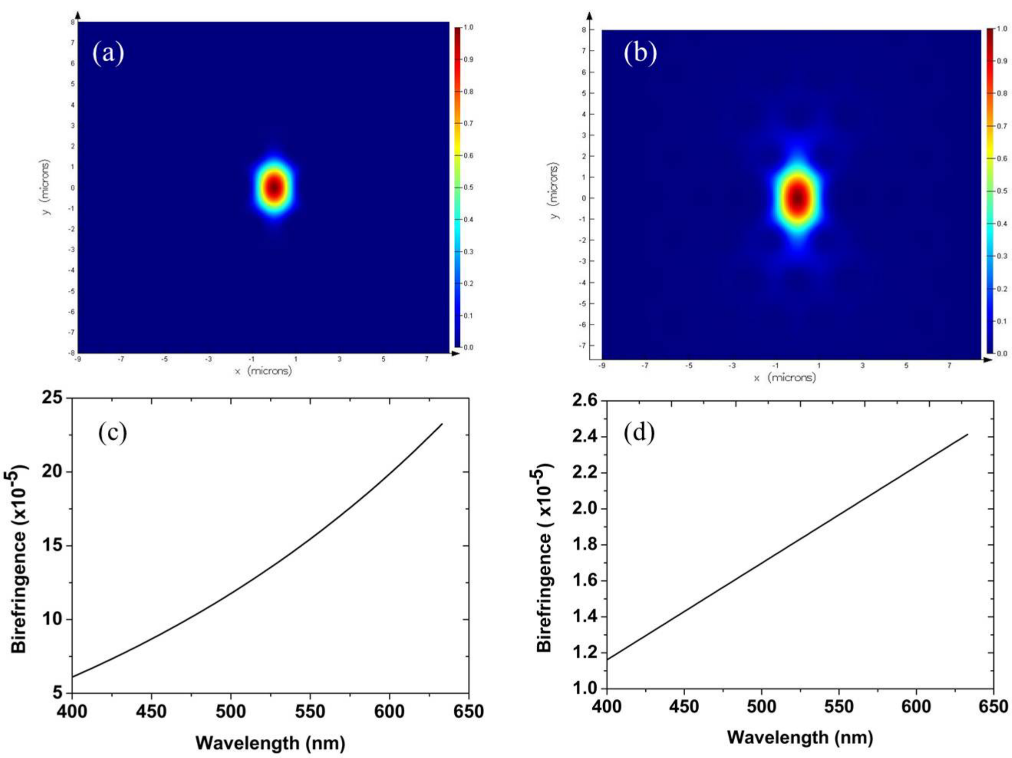

Figure 2 Fundamental mode profile of (a) conventional Hi-Bi PCF and (b) hybrid PDMS/Silica PCF at 633 nm. Birefringence versus wavelength of (c) the conventional Hi-Bi PCF and (d) hybrid PCF from 400 to 633 nm wavelength.

In the following part, we consider the temperature dependence of birefringence of the hybrid Hi-Bi PCF for a range of temperatures from 20-120°C. PDMS has high negatively linear thermo-optic coefficient[19] which is $dn/dT = -4.5\text{x}10^{-4}$ /°C. We calculate the effective index of the fundamental mode for every 10°C considering as room temperature 20°C. Figure 3 shows the variation of the birefringence with respect the temperature for a fixed wavelength of 633 nm. Since the refractive index contrast between cladding-core increases as temperature increases, consequently the birefringence is becoming stronger. As can be clearly seen, the birefringence is less than $4\text{x}10^{-5}$ at around room temperature, while at 80°C is doubled. The high thermo-optic coefficient of the elastomer inclusions into the PCF, provide the ability to the fiber to act either as tunable device or as a temperature sensor. It should be mentioned that in our calculation we consider silica to be totally insensitive to temperature variations.

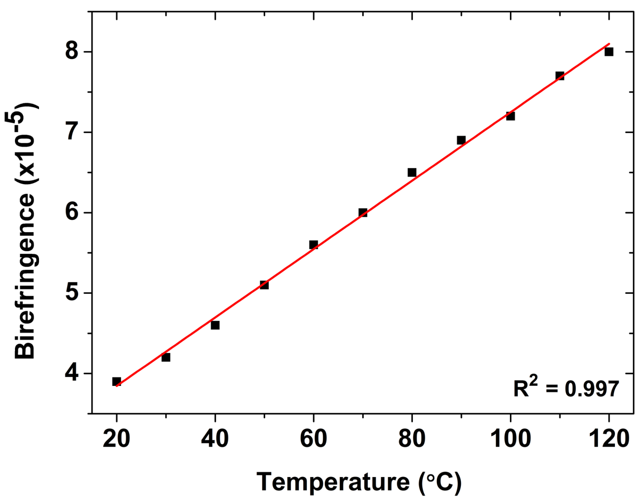

Figure 3. Birefringence versus temperature of the hybrid PDMS/Silica Hi-Bi PCF (square dots correspond to calculated data and red solid line to linear fitting).

1.2 Experiment

In this section, we demonstrate the experimental investigation of the birefringent properties of the hybrid PDMS/Silica PCF against temperature variations, using a polarized laser source at 633 nm, a λ/2 waveplate and a polarization analyser as shown in Figure 4. The hybrid Hi-Bi PCF was placed on top of a temperature-controlled peltier element with perfect thermal contact to the surface. By launching linear polarized light at 45° to the principal axis a single-fiber interferometer was formed where the two orthogonal linear polarizations constitute the two arms of the interferometer. The output intensity passing the analyzer at 45°, as the temperature changes, can be expressed as:

$$I = I_o \cos^2\left(\frac{\varphi(T)}{2}\right) \tag{2}$$

I_o is the total output power and φ(T) is defined as:

$$\varphi(T) = \frac{2\pi B(T)L}{\lambda} \tag{3}$$

where B, L and λ are the birefringence, length of fiber, and wavelength, respectively. It should be noted here that the validity of Eq. (2) is restricted to fibers exhibiting only linear birefringence.

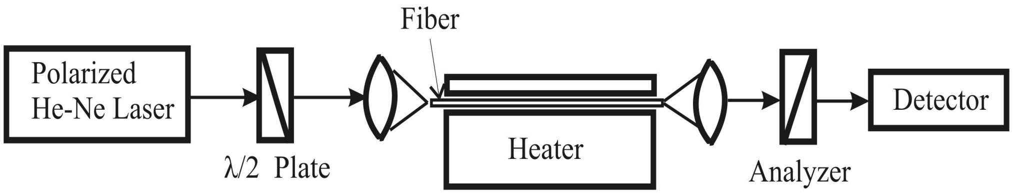

Figure 4. Experimental set-up

Figure 3(b) shows the output power indicating the sinusoidal variation for temperatures ranging from 20 to 80°C. Birefringent properties of the hybrid PCF are experimentally demonstrated at 633 nm where the absorption loss of the elastomer material is very low. Slight discrepancies appeared in our experimental results derived from a combination of losses such as power fluctuations, coupling in/out instabilities, etc. In general, the sensitivity can be defined as the phase shift of the polarization state over temperature for a given length of fiber[20] (see reference for detailed analysis). In our experiments, the measured sensitivity was found to be 0.37 rad/K/cm for a 1.4 cm fiber length, which is significant higher compared to a conventional Hi-Bi fiber[20].

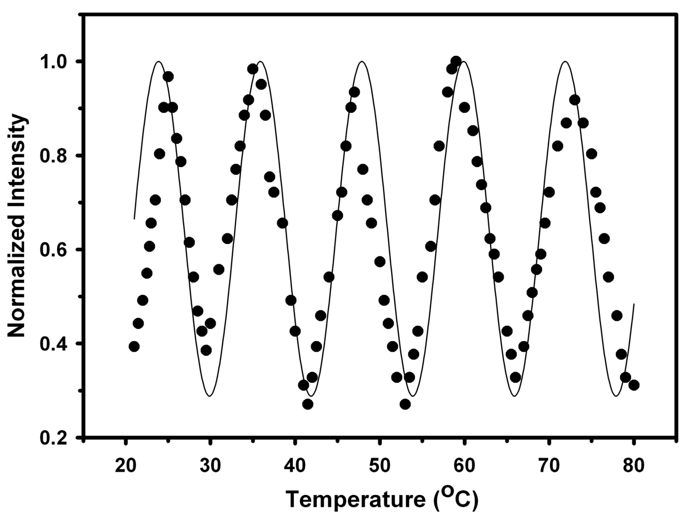

Figure 5. Measurement of the one-fiber interferometer containing the hybrid PCF at different temperatures (dots correspond to measured data and solid line corresponds to sine squared fitting function).

4. CONCLUSION

We have presented results that report the fabrication of a hybrid PDMS/Silica Hi-Bi PCF for the first time. The guiding and birefringent properties of the hybrid structure have been investigated using a commercial fully vectorial mode solver. Furthermore, we have experimentally characterized the birefringent dependence of the hybrid PDMS/Silica fiber with temperature variation from 20 to 80°C exhibiting high sensitivity of 0.37 rad/K/cm. One of the main advantages of the presented work is the direct modification of conventional temperature insensitive Hi-Bi PCF to highly sensitive over short lengths, simply by infiltrating the PCF with a widely used commercial elastomeric material. Further characterization of the hybrid PDMS/Silica fiber in terms of polarization properties is underway.

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