Thermo-optic effect of an index guiding photonic crystal fiber with elastomer inclusions

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ABSTRACT

In this work, we demonstrate numerically and experimentally the temperature dependence of a photonic crystal fiber (PCF) infiltrated with PDMS elastomer. We investigated the guiding properties of the PDMS-filled PCF and we present the variation of the effective index and effective modal areas of the fundamental guiding mode at 633 and 1550 nm, for a range of temperatures from 20°C to 75°C. Experimental measurements have shown an up to ~6% power recovery of the bend-induced loss for a 6-cm long PDMS-filled PCF at 4 cm bend diameter.

Keywords: Photonic crystal fiber, polymer material, temperature device

1. INTRODUCTION

Infiltration of advanced materials into the air holes of the PCFs can potentially manipulate their optical properties. Many devices such as switches [1], tunable devices, sensors [2-5] have been developed and studied by filling liquid crystal, high index fluids, as well as other materials into the air holes by transforming an index guiding PCF into a photonic bandgap fiber (PBG) [6].

PDMS (poly-dimethylsiloxane) elastomer is widely used in the area of photonics, particularly in opto/microfluidics, having unique optical properties. Transparency for a wide range of wavelength, lower refractive index (around 1.41) than fused silica, high elasto-optic and thermo-optic coefficients, biocompatibility, minimal loss due to absorption, are some of its features. It also exhibits very good mechanical properties due to low Young's modulus; it is soft and deformable with no shrinkage and combined with its ease fabrication procedure is a potential active material for tunable devices and sensing applications [7].

In this paper, we demonstrate the combination of the aforementioned polymeric material with PCF. Numerical simulations performed in order to investigate the temperature dependence of the PDMS-filled PCF. The negatively high linear thermo-optic coefficient of the elastomeric inclusions can partially reconstruct the fundamental guiding mode where experimental measurements of a bent (at 4 cm bend diameter) PDMS-filled PCF exhibited partial recovery of the transmitted power for a range of temperatures up to 75°C.

2. EXPERIMENTAL

We employed a commercial PCF (Crystal Fibre A/S) with a core diameter of about 12 μm in which the air holes with diameter 3.5 μm are arranged in a hexagonal pattern with a pitch of 7.7 μm, as shown in figure 1(a). PDMS (Dow-Corning) was prepared by mixing elastomer and curing agent at 10:1 ratio. Figure 1(b) shows the scanning electron microscopy (SEM) image of the infiltrated PCF with PDMS; the fully filled part of the PCF had a length of about 6 cm.
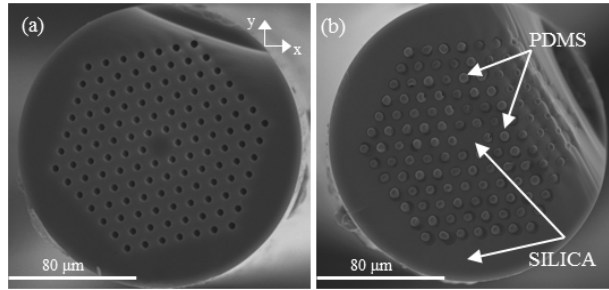
Fig 1. SEM image of: (a) a conventional PCF. (b) PDMS-filled PCF.

3. RESULTS AND DISCUSSION

3.1 Guiding properties of PDMS-filled PCF

FDTD analysis was performed using the commercial software package *Lumerical FDTD Solutions* [8] in order to investigate the guiding mechanism of the PDMS-silica structure. PDMS-filling fraction corresponded to 18.73%, where the low refractive index difference between silica and elastomer reduces the confinement of the fundamental guiding mode. Figures 2(a)-2(b) illustrate the simulated mode profiles of the PDMS-filled PCF at 633 and 1550 nm, respectively. The effective modal areas were calculated to be Aeff $\approx$ 81.75μm^2 and 126.98 μm^2, at the aforementioned wavelengths, while for a conventional PCF these are Aeff $\approx$ 70.08μm^2 and 74.68μm^2, respectively. Figure 2(c) shows the experimental near-field intensity pattern of the fundamental mode at 633 nm wavelength captured using a CCD camera. The calculated effective indices of the conventional and PDMS/silica PCF are shown in Figure 2(d) for a broad range of wavelengths. Real and imaginary parts of the refractive index of PDMS - were calculated using the Sellmeier equation, where the coefficients have been experimentally determined in [9]. Cut-back technique used in order to measure the total transmission loss of PDMS-filled fiber found to be around ~0.06 dB/cm at 633 nm wavelength. Absorption coefficient of the material at this wavelength is very small [9]. At 1550 nm, transmission loss was increased to ~0.17 dB/cm, since the confinement of the fundamental core mode was reduced, as compared to short wavelengths and the absorption coefficient of the material at infrared (IR) wavelengths is higher.
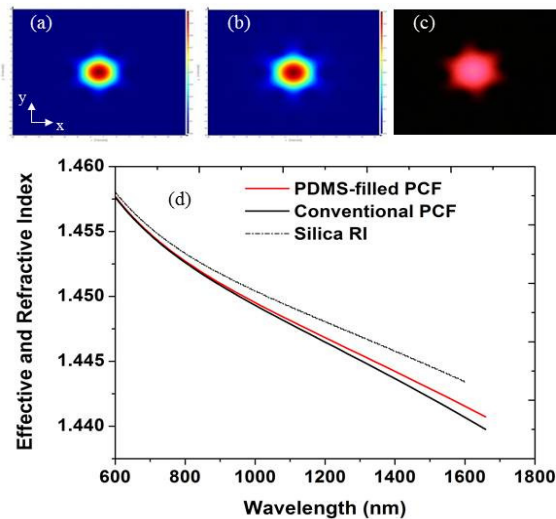

Fig. 2. (a) Calculated fundamental mode profile of the PDMS-filled PCF at 633 and (b) 1550 nm wavelength. (c) Experimental near field fundamental mode field pattern at 633 nm wavelength, captured with a CCD camera. (d) Effective indices of a conventional (black line) and PDMS-filled PCF (red line). (Refractive index of fused silica is also included into the plot for reference purposes).

3.2 Thermo-optic effect

The temperature dependence of the refractive index is defined by the thermo-optic coefficient dn/dT, which is based in change of the refractive index arising from an infinitesimal change of the temperature. The PDMS elastomer, among the others optical properties mentioned previously, also exhibits a highly linear, negative thermo-optic coefficient corresponding to dn/dT = -4.5x10-4/ °C [10]. Based on numerical analysis, we have calculated the effective index of the fundamental guiding mode of the PDMS-filled PCF as a function of temperature from 20°C to 75°C at 633 and at 1550 nm (see Figure 3(a) and (b)). Δneff is almost an order of magnitude higher at 1550 nm, due to the low mode confinement and the large overlap between the guiding mode and cladding. Figure 3(c) shows the effective modal area of the hybrid PCF for the same range of temperatures at 633 and 1550 nm.
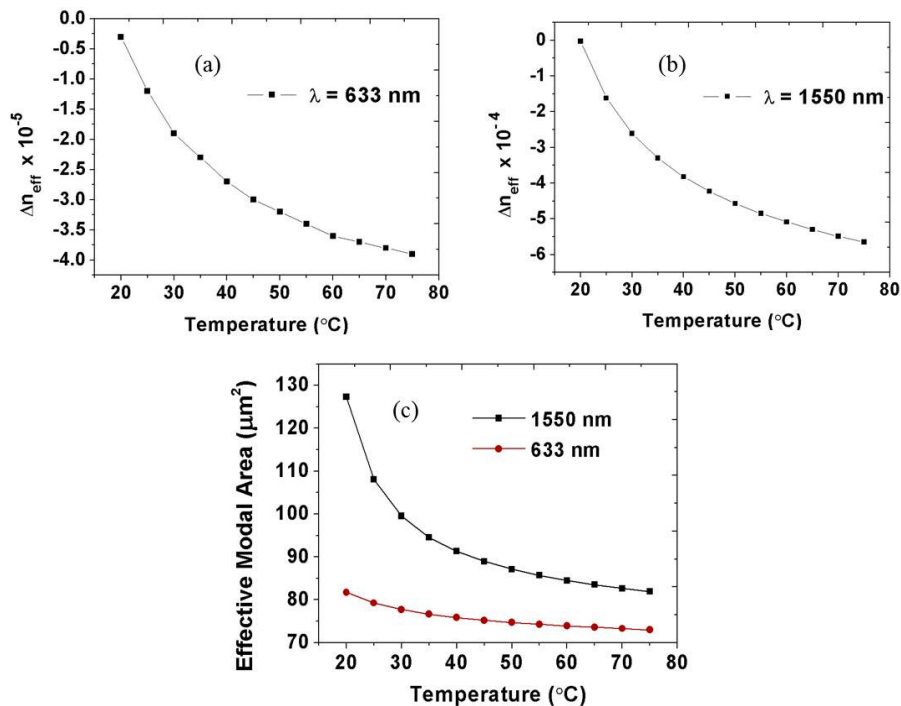

Fig. 3. Effective index Δneff of PDMS-filled PCF as a function of temperature at (a) 633 nm and
(b) 1550 nm operating wavelength. (c) Effective modal areas at 633 and 1550 nm wavelength.

The thermo-optic sensitivity of the hybrid PCF, induced by the elastomer inclusion, was also investigated experimentally. We placed the hybrid PCF at a bend diameter of 4 cm on top of a peltier element with perfect thermal contact to the surface. Using a laser source, a power meter, and a thermo-couple we measured the amount of power recovered from the bending induced loss. Figure 4(a) shows how bending loss varies with the increase of temperature at 633 nm and clearly shows a recovery of ~3.6 % of the total transmitted power, at 75°C. Same measurements were repeated at 1550nm, investigating the thermo-optic sensitivity at longer wavelengths and the bend-induced power loss recovery corresponded to 5.93%. Results are shown in Figure 4(b). Slight discrepancies appeared in our experimental results derived from a combination of losses arising in the fabrication process and experimental characterization of the device (absorption due to impurities, scattering, human error, etc.). The temperature sensitivity was defined as ΔPower/ΔTemp and estimated to be 0.05 dB/°C at 633 nm and 0.005 dB/°C at 1550 nm. In the case of the conventional PCF, power was unrecoverable either at 633nm or 1550 nm wavelength due to very small thermo-optic coefficient of fused silica [11].
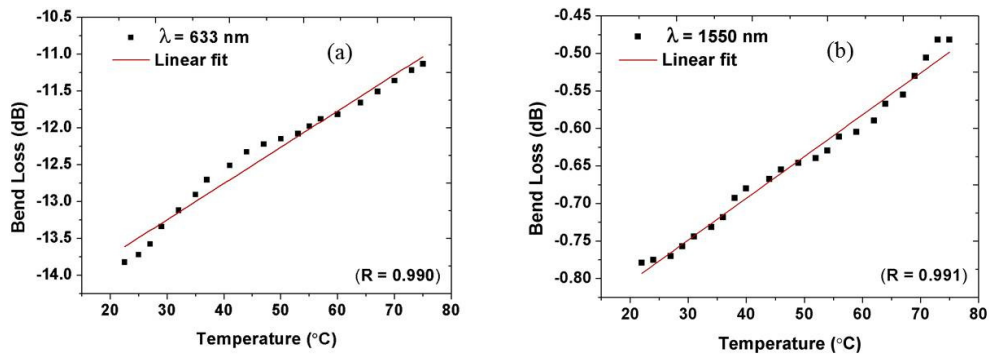
Fig. 4. Thermo-optic effect of PDMS-filled PCF for a bend diameter of 4 cm at (a) 633 and (b) 1550 nm.

3. CONCLUSION

In conclusion, we have demonstrated the properties of an infiltrated PCF with PDMS elastomer. We examined the guiding mechanism of the fiber and we measured low level of loss over short lengths. Numerical calculations indicated the dependence of the effective index and modal areas of PDMS/silica PCF with temperature and we demonstrated experimentally how the fundamental mode of a bent fiber can be reconstructed due to thermo-optic effect of the PDMS inclusions into PCF's holes. An up to ~ 6% bend-induced power loss recovery at a range of temperatures up to 75°C demonstrated. The PDMS-filled PCF has the ability to act as temperature-tuned device over a wide range of wavelengths while it is relatively simple to be developed using commercially available PCFs and a low cost elastomer material.

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