Optical switch based on a fluid-filled photonic crystal fiber Bragg grating

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We report the implementation of an in-fiber optical switch by means of filling a fluid into the air holes of a photonic crystal fiber with a fiber Bragg grating. Such a switch can turn on/off light transmission with an extinction ratio of up to 33 dB within a narrow wavelength range (Bragg wavelength) via a small temperature adjustment of ±5 °C. The switching function is based on the temperature-dependent coupling between the fundamental core mode and the rod modes in the fluid-filled holes resulting from the thermo-optic effect of the filled fluid. © 2009 Optical Society of America

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In-fiber switches based on optical fiber gratings have been demonstrated in all-optical communications networks [1,2]. Unique microstructures in photonic crystal fibers (PCFs) allow various advanced materials to be filled into the air holes of PCFs, offering new platforms for developing innovative optical switches. An index-guiding PCF may be transformed into an all-solid photonic bandgap fiber (PBF) by filling high-index material into the air holes. Such an invertible transformation in the fiber types (PCF/PBF) has led to many switching applications [3–6]. These switches, however, usually turn on/off the light transmission over a broad wavelength range and cannot perform the switching function within a narrow wavelength range. In this Letter, we demonstrate a thermo-optic in-fiber optical switch produced by filling immersion oil into the air holes of a solid-core PCF in combination with an FBG. Such a switch can turn on/off light transmission within a narrow wavelength range (Bragg wavelength) as the result of the coupling between the fundamental core mode and the LP_{01}-like mode in the fluid rods.

A solid-core Ge-doped PCF (IPHT-252b5) with a core diameter of 4.1 μm was employed in our experiments. Air holes of the PCF have an average diameter of 3.5 μm and are arranged in a hexagonal pattern with an average pitch of 4.2 μm. Other parameters of the PCF are listed in Table 1 of [7]. The PCF has a low transmission loss within a broad wavelength range, as shown in Fig. 1(a). The central region of the fiber core with a diameter of about 0.5 μm was doped with a high concentration of germanium (36 mol.%). The calculated refractive indices of the Ge-doped core and of the pure silica (SiO_2) cladding are $\approx$1.5039 and 1.4538, respectively, at a wavelength of 830 nm.

As shown in Fig. 1(b), an FBG with a reflectivity of 45%, a Bragg wavelength of 829.76 nm, and a grating length of $\approx$6 mm was inscribed in the Ge-doped small-core PCF by the use of a 248 nm KrF excimer laser [8]. One end of the PCF with the FBG was spliced to a standard single-mode fiber (SMF) with a splice loss of $\approx$1.0 dB using the arc fusion splicing technique as reported in [9]. Another end of the PCF with a length of 300 mm was cleaved at a distance of 5 mm from the FBG and then placed in an immersion oil ($n = 1.482$ at room temperature; http://www.niepoetter.de). Thus the immersion oil was filled into the air holes of the PCFs by means of the well-known capillarity action. The actual fluid-filled PCF including the FBG had a total length of $\approx$150 mm.

Then we investigated the response of the fluid-filled FBG to the temperature change using a semiconductor Peltier cooler, a temperature controller (THORLABS TED200), and a specifically adapted FBG interrogation system [7]. As shown in Fig. 2(a), in the case of the temperature rising from 25 °C to 80 °C, a minor change occurred in the relative reflection intensity of the fluid-filled FBG, and the corresponding Bragg wavelength shifted linearly toward the longer wavelength with a sensitivity of 5.4 pm/°C. It is interesting to see in Fig. 2(a) that the reflection intensity gradually decreased, increased, and decreased again as the temperature changed from 25 °C to 0 °C. In other words, the reflection peak of the fluid-filled FBG gradually disappeared, reappeared, and disappeared again in the temperature range from 25 °C to 0 °C. No reflection peak was observed for temperatures between 13°C and 18 °C. Similar developments in both Bragg wavelength and peak reflection intensity were observed during the temperature increase (T_up: ▲ and ◆) or decrease (T_down: ▼ and ■). As shown in Fig. 2(b), perfect reflection peaks were observed at 9°C and 25 °C, and the Bragg reflection peak disappeared completely at 16 °C. The fluid-filled PCF (FBG) can, therefore, be used to develop a promising in-fiber optical switch. Such an optical switch can turn on/off light transmission within a narrow wavelength range

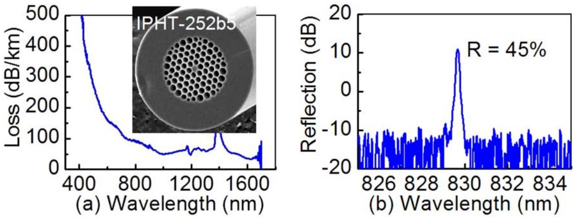

Fig. 1. (Color online) (a) Transmission loss of the PCF (IPHT-252b5 from Institute of Photonic Technology, http://www.ipht-jena.de), the inset being a cross-section image of the PCF. (b) Reflection spectrum of the FBG inscribed in the PCF.

(Bragg wavelength) via a small temperature adjustment of ±5 °C.

The refractive indices and the absorption properties of the employed immersion oil at different temperatures were investigated with an automatic refractometer (J357) and a Jasco Fourier transform infrared spectrometer (FT/IR-6300), respectively. As shown in Fig 3(a), the refractive index of the oil is $n = 1.482$ at room temperature and decreases linearly with a slope of $-3.76 \times 10^{-4}/{}^{\circ}\mathrm{C}$ when the temperature rises. As shown in Fig. 3(b), the fluid has a low absorption near 830 nm at room temperature. Moreover, no relevant changes were observed for the absorption curves of the fluid at different temperatures, indicating that the absorption of the fluid stays almost constant with increasing temperature.

To explain the switching function of the fluid-filled FBG, we numerically calculate modal maps, i.e., effective-index curves, for the modes in the fluid-filled PCF (FBG) at different temperatures by the use of a finite-element method (FEM) software package, as shown in Fig. 4. The temperature-dependent properties of the fluid material, the Ge-doped core, and the pure silica background are taken into consideration in the calculations. For the fluid-filled PCF, two different modes are considered: the core mode and rod modes [10]. The core mode is determined by the index difference between the Ge-doped core and the pure silica background. The so-called rod modes correspond to light guided in the fluid rods and exist in the form of discrete bands as a result of the strong coupling between the adjacent fluid rods. Each rod mode band contains many rod modes with close effective indices. For a specific rod mode in a certain band ($LP_{01}, LP_{11}, \ldots .$), electric field profiles are the same in all the rods, though with different phase relationships [10]. The curves of the core mode and the rod mode bands cross each other at some certain wavelength ranges, e.g., near 830 nm in Fig. 4(b), in which the core mode and the rod modes are coupled to each other and form a “mixed mode” profile. The effective indices of the rod modes are determined by the refractive index of the fluid rods, and therefore are tunable due to the thermo-optic effect of the fluid. Thus, the coupling wavelength range can be thermally controlled.

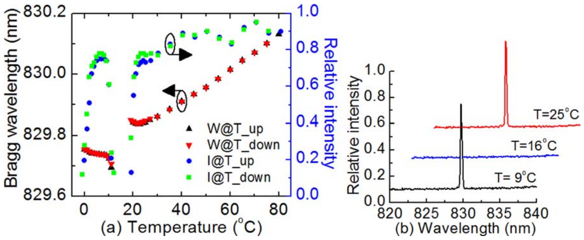

Fig. 2. (Color online) (a) Developments in the Bragg wavelength (▲ and ▼) and the relative reflection intensity (■ and ♦) of the fluid-filled PCF (FBG) with an increased (T_up: ▲ and ♦) or decreased (T_down: ▼ and ■) temperature. (b) Reflection spectra of the fluid-filled PCF (FBG) at 9°C, 16°C, and 25 °C.

Based on the modal analysis of the fluid-filled PCF above, as shown in Fig. 5(a), we numerically simulated the evolution of the Bragg wavelengths and the reflection properties of the FBG with temperature. Figures 5(a) and 2(a) show a good agreement between the numerical simulation and the experimental results with regard to Bragg wavelength and reflection. For a higher temperature, e.g., 25 °C, the core mode around the Bragg wavelength of 830 nm is well confined in the Ge-doped core, as shown in Fig. 4(c). Thus a high overlap integral can be achieved, which corresponds to an “on” state of the FBG switching. When the temperature is ≈16 °C, the core mode light is coupled into LP_{01} rod modes because of the mode crossing between the core mode and the LP_{01} rod mode band around the Bragg wavelength of 830 nm, as shown in Fig. 4(b). As a result, the reflective peak disappears because of a near-zero overlap between the core mode and the Ge-doped region. Thereby, the “off” state of the FBG switching is obtained. For a lower temperature, e.g., 9 °C, the effective index curve of the core mode around the Bragg wavelength of 830 nm is located between the LP_{01} and LP_{11} rod bands, as shown in Fig. 4(a). Thus no light is coupled into the rod modes because of the mode separation, and a high overlap integral between the core mode and the Ge-doped region is reachieved. As a result, the “on” state of the FBG switching is obtained again. As the temperature further decreases to an extremely low temperature, e.g., 0 °C, the reflection intensity of the FBG will be reduced again as a result of the energy coupling from the core mode to the LP_{11} rod mode, as shown in Figs. 2(a) and 5(a), resulting from the crossing between the core mode and the LP_{11} rod mode band around the Bragg wavelength of 830 nm.

For the temperature range from 25 °C to 80 °C in which the core mode is well confined in the Ge-doped core, as shown in Figs. 2(a) and 5(a), the Bragg wavelength of the fluid-filled FBG shifted linearly

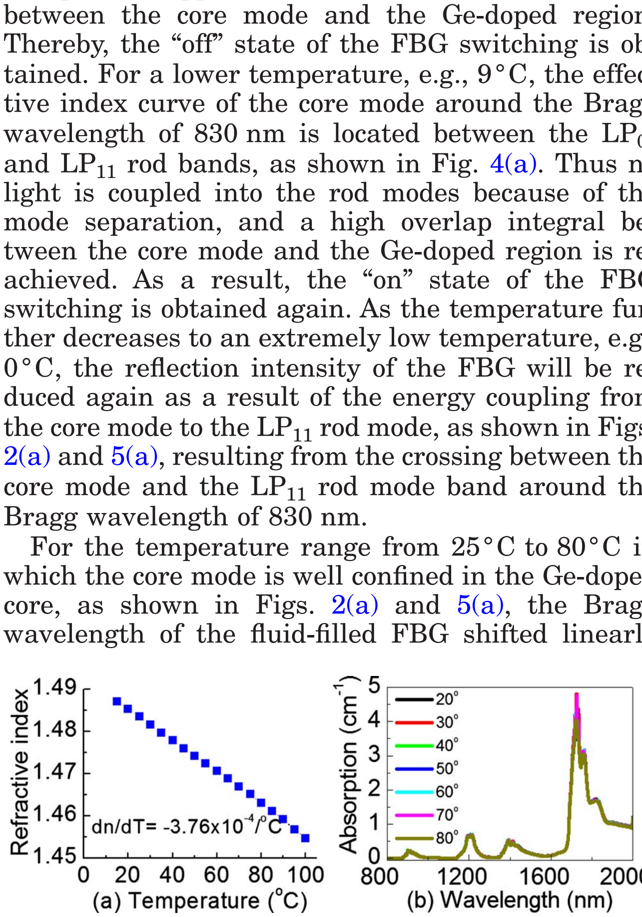

Fig. 3. (Color online) (a) Refractive index change of the immersion oil with rising temperature. (b) Absorption coefficients of the immersion oil at different temperatures.

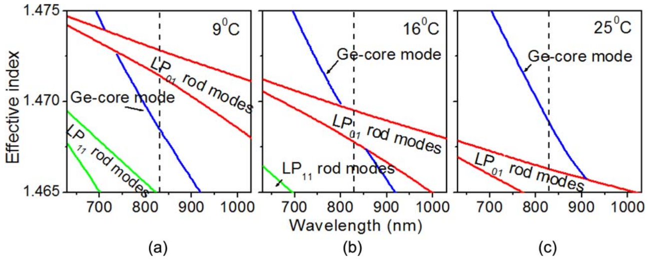

Fig. 4. (Color online) Calculated modal maps for the fluid-filled PCF (FBG) at temperatures of (a) 9 °C, (b) 16 °C, (c) 25 °C. The vertical dashed line illustrates the Bragg wavelength of the FBG.

toward the longer wavelength with a sensitivity of 5.4 pm/°C, showing a good agreement with the temperature sensitivity (5.5 pm/°C) of the FBG in the same type of an unfilled PCF [7]. This indicates that the temperature sensitivity of the FBG inscribed in the PCF is but little affected by the filled fluid in the air holes, provided that the core mode is well confined in the Ge-doped core. However, for the temperature at which the "mixed" modes as combinations of rod and core modes exist, the evolution of the Bragg wavelength is quite different between the core modes and the liquid-rod modes as a result of the so-called "avoided crossing effect". For the temperature range from 25 °C to 18 °C, the light in the core mode is gradually coupled into the rod modes with decreasing temperature, which is a so-called transition state between the "on" and "off" states of the proposed switching function. For example, the mode energy is observed in both the Ge-doped core and the cladding liquid rods at 20 °C, as shown in Fig. 5(b), resulting from the light coupling from the core mode to the rod modes because of the existence of "mixed" modes.

In conclusion, the fluid-filled PCF in combination with an FBG can be used to develop a promising thermo-optic in-fiber optical switch as the result of the temperature-dependent coupling between the fundamental core mode and the rod modes. The extinction ratio of the proposed switch depends strongly on the mode energy in the Ge-doped core at the "on" and "off" switching states, and is theoretically calculated to be as high as 33 dB. Such a switch can turn on/off light transmission within a narrow wavelength range (Bragg wavelength) via a small temperature variation of ±5 °C.

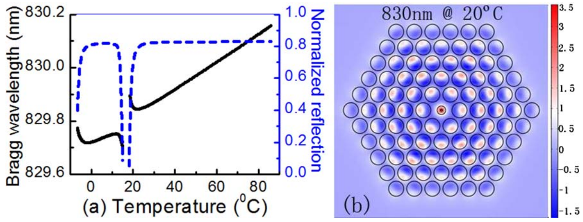

Fig. 5. (Color online) (a) Calculated evolutions of Bragg wavelength (solid curve) and normalized reflection (dashed curve) for the fluid-filled FBG as a function of temperature. (b) Simulated mode energy distribution within the cross section of the fluid-filled PCF at 830 nm for an E_x field at 20 °C.

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