Temperature-controlled transformation in fiber types of fluid-filled photonic crystal fibers and applications

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We investigated experimentally and theoretically an invertible fiber-type transformation from a photonic bandgap fiber into a nonideal waveguide and then into an index-guiding photonic crystal fiber via the thermo-optic effect of the fluid filled in the air holes. Such a transformation could be used to develop an in-fiber optical switch/attenuator with a high-extinction ratio of more than 35 dB over an extremely broad wavelength range from 600 to 1700 nm via a small temperature adjustment. © 2009 Optical Society of America

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Unique microstructures in photonic crystal fibers (PCFs) allow various advanced materials to be filled into their air holes. Many in-fiber devices such as switches [1–4], attenuators [5], and dispersion compensators [6] have been developed by filling liquid crystal, refractive-index-matching liquid, and other materials into the air holes to transform an index-guiding PCF into a photonic bandgap fiber (PBF). All of these functions are attributed to the bandgap changes resulting from the thermo-optic effect of the filled fluid and are usually operated within a limited wavelength range [1–6]. The fiber type transformation from a PCF into a PBF should be an invertible process resulting from increasing/decreasing the refractive index of the filled materials. Such an invertible transformation in the fiber types (PCF/PBF) may lead to many potential applications. Research [1–6] was, however, focused on the transformation from an index-guiding fiber to a bandgap-guiding fiber instead of an opposite process.

In this Letter, we filled a fluid into the air holes of a solid-core PCF and investigated experimentally and theoretically an invertible fiber-type transformation from a PBF into an unideal waveguide and then into an index-guiding PCF via the thermo-optic effect of the filled fluid. Such a fluid-filled PCF could be used to develop an in-fiber optical switch/attenuator with a high extinction ratio of more than 35 dB over an extremely broad wavelength range from 600 to 1700 nm.

We employed a large-mode area PCF (LMA-10 from Crystal Fibre) with a core diameter of about 5.9 μm in which the air holes with a diameter of 3.2 μm are arranged in a hexagonal pattern with a pitch of 7.5 μm, as shown in Fig. 1(a). One end of the PCF with a length of 500 mm was spliced to a standard single-mode fiber (SMF) with a splice loss of about 1.5 dB using the arc fusion-splicing technique [7]. Another end of the PCF was cleaved and then immersed into a refractive-index-matching liquid with a thermo-optic coefficient of $-4.15\times10^{-4}/°\mathrm{C}$ from Cargille Labs ($n=1.550$ at room temperature, http://www.cargille.com). The fluid was filled into air holes in the PCF with the well-known capillary action, as shown in Figs. 1(b)–1(d). The fully filled PCF has a total length of about 200 mm.

Then the opening end of the fluid-filled PCF was butt-coupled to another conventional SMF in order to investigate its transmission spectrum with a supercontinuum white-light source (KOHERAS SuperK Compact) and an optical spectrum analyzer (ANDO AQ6317B). The fluid-filled PCF was placed in a column oven (LCO 102) to investigate its transmission spectra at different temperatures. Figure 2(a) illustrates the measured transmission spectra of the fluid-filled PCF at temperatures of 20°C, 60°C, and 100°C, where the total insertion loss of about 5 dB is attributed to the coupling losses between the PCF and the two SMFs. As shown in the transmission spectrum at 20°C, three clear attenuation gaps were observed within the wavelength range from 750 to 820 nm, from 950 to 1050 nm, and from 1300 to 1550

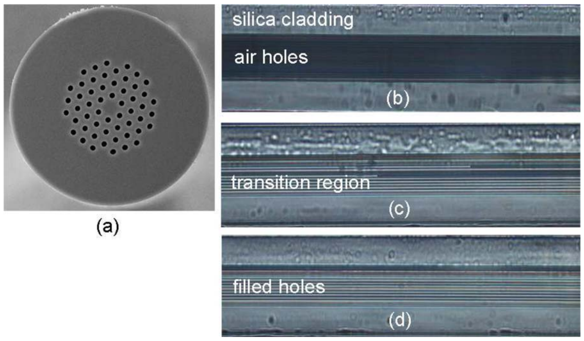

Fig. 1. (Color online) (a) Cross-section image of the PCF; side images of (b) the unfilled PCF, (c) the transition region between unfilled and fully filled air holes, and (d) the fully filled PCF, where (b), (c), and (d) were observed by the use of a microscope (Nikon ECLIPSE 80i) whose focal plane was adjusted to the fiber axis.

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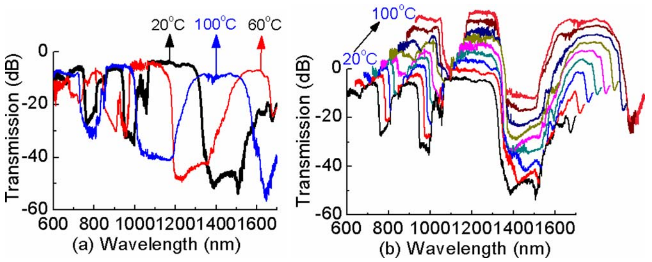


Fig. 2. (Color online) (a) Transmission spectra of the fluid-filled PCF ($n=1.550$ at 20°C) at temperatures of 20°C, 60°C, and 100°C; (b) transmission spectrum evolution of the fluid-filled PCF with rising temperature from 20°C to 100°C with a step of 10°C.

nm, respectively. In other words, several bandgaps occurred within the measured wavelength range at 20°C. Hence, the fluid-filled PCF is a so-called bandgap-guiding fiber, i.e., a PBF. The extinction ratio of the bandgap at the longer wavelength is as high as about 40 dB. It is interesting to see from Fig. 2(b) that the bandgaps shifted toward the shorter wavelength with the rising temperature resulting from the thermo-optic effect of the filled fluid. Moreover, the bandgap within the wavelength range of more than 1400 nm gradually broadened with the rising temperature and was completely observed at 100°C. In contrast, the bandgaps within the wavelength range of less than 1400 nm gradually narrowed and even disappeared with the rising temperature.

In order to investigate further the effect of the thermo-optic effect of the filled fluid on the transmission properties of the fluid-filled PCF, we filled another refractive-index-matching liquid with a lower index ($n=1.480$ at 20°C with a temperature coefficient of $-3.95\times10^{-4}/°\mathrm{C}$) into air holes of the same type of PCF with the same method above. The length of the actual fluid-filled PCF is also about 200 mm. As can be seen from the transmission spectrum of the fluid-filled PCF in Fig. 3(a), two attenuation gaps were respectively observed within the wavelength range from 700 to 800 nm and from 1000 to 1450 nm at 20°C. In other words, three main bandgaps occur within the measured wavelength range at 20°C. As shown in Fig. 3(a), the bandgaps shifted toward the shorter wavelength and disappeared gradually with the rising temperature from 20°C to 70°C. Furthermore, the bandgaps disappeared completely when the temperature rose to 75°C, as shown in Fig. 3(b). In other words, the light transmitted in the fiber core was completely attenuated within the whole wavelength range of 600 to 1700 nm at 75°C. It is interesting to see from Fig. 3(b) the light at the shorter wavelength appeared gradually with the rising temperature from 75°C to 130°C. Moreover, the higher the temperature is, the wider the transmission range is. Especially, no obvious attenuation was observed within the whole wavelength range of 600 to 1700 nm when the temperature rose to 130°C.

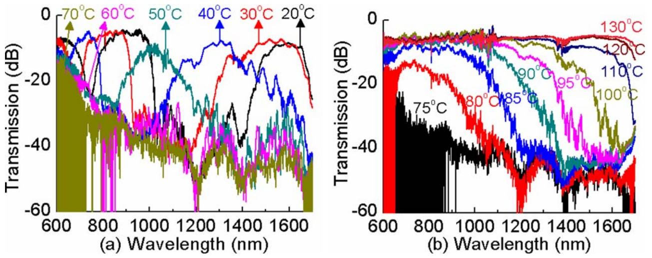
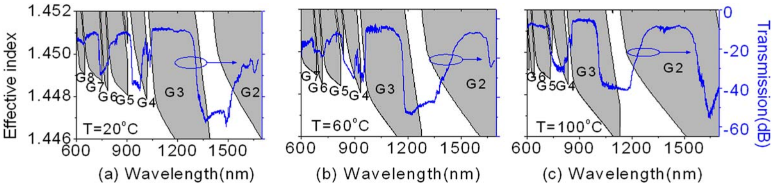


Fig. 3. (Color online) Transmission spectra of the fluid-filled PCF ($n=1.480$ at 20°C) at different temperatures from (a) 20°C to 70°C and (b) from 75°C to 130°C.

We numerically calculated modal maps, i.e., effective-index curves, for the modes in the fiber at different temperatures with a plane-wave-expansion method [8], as shown in Fig. 4. The temperature-dependent properties of both the filled fluid and the pure silica background are taken into consideration in the calculations. The measured transmission spectra of the fluid-filled PCF at the corresponding temperatures are also illustrated in Fig. 4 to compare with the calculated results. As can be seen from Fig. 4(a), seven bandgaps (G2, G3,…, and G8) were observed in both the calculated modal maps and the measured transmission spectra at 20°C within the wavelength range from 600 to 1700 nm. It is obvious that the simulation results and the experimental measurements show, in general, a good qualitative agreement. In our experiments, since the resolution of the optical spectrum analyzer (OSA) employed was adjusted to 1 nm to decrease the measurement time due to the large measured wavelength range of more than 1 μm; the attenuation gaps between G3 and G4, between G5 and G6, and between G7 and G8 were not clearly illustrated in the transmission spectra. As shown in Fig. 4, the even-numbered bandgaps have, in general, higher losses than the odd-numbered bandgaps due to stronger coupling with the cladding mode [9]. As shown in Figs. 2 and 4, the bandgaps shift gradually toward the shorter wavelength with the rising temperature resulting from the decreased refractive index of the filled fluid due to the thermo-optic effect. As a result, the seventh and eighth bandgaps, G7 and G8, disappear within the measured wavelength range from 600 to 1700 nm at a higher temperature of 100°C. The small difference between the calculated bandgap maps and the measured transmission spectra may be attributed to the unknown dispersion properties of the fluid employed, which is ignored in our calculations.

As shown in Figs. 3(b) and 5, the calculated and measured spectra of the fluid-filled PCF at different temperatures show a good qualitative agreement. Our fluid-filled PCF was actually a bandgap-guiding fiber due to the higher index in the fluid rods than in the pure-silica background of the PCF. Many bandgaps were therefore observed in the measured transmission spectra of the fluid-filled PCF, as shown in Fig. 3(a). When the temperature rises to about 75°C, the refractive index of the filled fluid in the holes is decreased and approximates that of the pure-silica background. In other words, the fluid-filled PCF is actually not an ideal waveguide near 75°C. As a result, we failed to find a fundamental mode in our calculation, so no calculated transmission spectrum near 75°C is illustrated in Fig. 5. As the refractive



(a) Wavelength(nm) (b) Wavelength(nm) (c) Wavelength(nm)

Fig. 4. (Color online) Calculated bandgap maps and measured transmission spectra of the fluid-filled PCF ($n=1.550$ at 20°C) at (a) 20°C, (b) 60°C, and (c) 100°C, where G2, G3,…, and G8 illustrate the second, third,…, and eighth bandgaps, respectively. Note that the first bandgap occurs near 3000.

index of the fluid decreases to a lower value than that in the pure-silica background with the temperature rising further, the fluid-filled PCF is gradually transformed into an index-guiding PCF. The light transmitted in the fiber core is therefore enhanced with the rising temperature from 80°C to 130°C, as shown in Fig. 3(b) and Fig. 5. As can be seen from the calculated transmission spectrum at 80°C in Fig. 5, the light transmission falls sharply near the cutoff wavelength of 1000 nm because the fundamental mode becomes weakly confined to the core [10]. Furthermore, the cutoff wavelength shifts to the longer wavelength with the rising temperature.

As shown in Fig. 3, over the extremely broad wavelength range from 600 to 1700 nm, the transmission spectrum of the fluid-filled PCF is about −40 dBm and about −5 dBm at the temperatures of 75°C and 130°C, respectively. The fluid-filled PCF therefore could be used to develop a promising in-fiber optical switch/attenuator with a high-extinction ratio of more than 35 dB. Such a switch/attenuator can turn on/off the light transmission over an extremely broad wavelength range from 600 to 1700 nm via a temperature adjustment from 75°C and 130°C. Although such a high temperature adjustment range may be not desired for a practical thermo-optic switch/attenuator, it can be decreased to a low temperature range near room temperature, providing the air holes of the PCF are filled by a fluid having the same refractive index as the pure-silica background of the PCF at room temperature.

Moreover, a narrowband in-fiber switching function can be realize at the desired single wavelength by means of integrating a suitable filter, e.g., a fiber Bragg grating, in the fluid-filled PCF. The temperature adjustment for realizing the single-wavelength-switching function can be decreased to a small range, depending on the actual operation wavelength. For example, a small temperature adjustment of ±5°C can realize a high-extinction ratio of 35 dB for a single-wavelength optical switch at the wavelength of 1550 nm, as shown in Fig. 3(b).

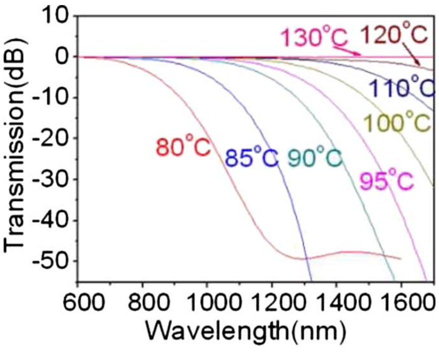


Fig. 5. (Color online) Calculated transmission spectra of the fundamental mode in the fluid-filled PCF ($n=1.480$ at 20°C) at different temperatures where the calculated fluid-filled PCF has a length of 100 mm.

In conclusion, the fluid-filled PCF is a bandgap-guiding fiber, i.e., PBF, at room temperature and can be transformed from a PBF into a nonideal waveguide and then into an index-guiding PCF via temperature adjustment. Such a transformation in the fiber types is an invertible process. The fluid-filled PCF could be used to develop a promising in-fiber optical switch/attenuator with a high-extinction ratio of more than 35 dB. Such a switch/attenuator can turn on/off the light transmission over an extremely broad wavelength range of more than 1 μm and could find useful applications in all-fiber optical communication systems.

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