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Compact tunable multibandpass filters based on liquid-filled photonic crystal fibers

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We demonstrated a compact tunable multibandpass filter with a short size of about 9 mm and a high wavelength-tuning sensitivity of up to −2.194 nm/°C by means of filling a liquid with a high refractive index of 1.700 into the air holes of a photonic crystal fiber (PCF). Such a PCF-based filter maintains an almost constant bandwidth and a large extinction ratio of more than 40 dB within the whole wavelength tuning range of more than 100 nm. Moreover, the transmission spectrum of the PCF-based filter is insensitive to the stretch force and the curvature of the fiber. © 2014 Optical Society of America

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Tunable fiber filters have been extensively used as key components in fiber-optic communication systems. A few methods have been demonstrated for obtaining tunable fiber filters that employed optical fiber gratings [1–4], combinations of different type of fibers [5], and optical fiber Fabry–Perot interferometers [6–8]. However, the characteristics of long-period fiber gratings are easily affected by external perturbations, such as tensile strain, pressure, and bend. Recently, with the development of photonic crystal fibers (PCFs) [9,10], a few types of tunable filters based on liquid-filled PCFs have been reported via the thermo- and electro-optic effects of the liquids [11–18]. This is due to the fact that an index-guided PCF can be transformed into a bandgap-guided photonic bandgap fiber (PBF) [11,15,16] by means of filling the air holes of the PCF with a liquid. As is well known, it is not easy to obtain a type of liquid with a higher refractive index, so the filling liquids have usually had a lower refractive index of about 1.550 in the previous experiments [11,14,15,19,20]. Consequently, the extinction ratio of the bandgap-based filters is sharply reduced with the rise in temperature due to the negative thermo-optic coefficient of the filling liquid. In addition, provided a liquid with a lower refractive index is employed, a longer PCF has to be filled to increase the extinction ratio of the bandgaps in the liquid-filled PCF, which is a disadvantage in the packaging of the bandgap-based filters and may result in a large liquid-induced absorption loss. Since it is difficult to splice a liquid-filled PCF with a single-mode fiber (SMF), the butt-coupling method is usually used to real-time monitor the optical properties of the PCF-based devices, which is not feasible in practical applications.

In this Letter, we demonstrate a compact tunable bandpass filter based on a liquid-filled PCF. Such a filter has a high extinction ratio of about 40 dB within an extremely broad wavelength range from 800 to 1700 nm. The splicing problem of the liquid-filled PCF is solved. Furthermore, we investigate the response of the PCF-based filter to temperature, strain, and bend.

We employed a large-mode-area pure silica PCF (ESM-12 from NKT, http://www.nktphotonics.com) with a core diameter of about 12 μm. Air holes with a diameter of 3.3 μm are arranged in a hexagonal pattern with a pitch of 7.4 μm, as shown in Fig. 1(a). One end of the PCF with a length of 70 mm was spliced to a standard SMF using a commercial arc fusion splicer (Fujikura FSM-60S). The discharge parameters of the splicer were modified to reduce the splice loss and to enhance the strength of the splicing joint [21,22]. Consequently, a low splice loss of about 0.5 dB at a wavelength of 1550 nm was achieved in our experiments, which is due to the optimized discharge parameters and the fact that the PCF employed has a similar mode field diameter (i.e., 10.5 μm at 1550 nm) to that of the standard SMF.

The other end of the PCF was immersed in a liquid (refractive index match liquid from Cargille Labs, http://www.cargille.com) with a very high refractive index of 1.700 and a thermo-optic coefficient of -4.79×10^{-4}/°C.

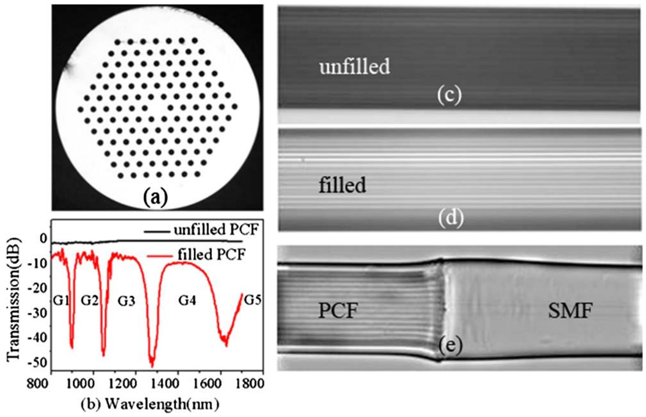

Fig. 1. (a) Cross-sectional image of the PCF employed, (b) transmission spectra of the filled and unfilled PCF, side images of (c) the unfilled PCF and (d) the fully filled PCF, and (e) the fusion joint of the PCF with a single mode fiber. G1, bandgap 1; G2, bandgap 2; G3, bandgap 3; G4, bandgap 4; G5, bandgap 5.

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Then the liquid was poured into the air holes of a PCF with well-known capillary action. If the filling time is about 5 min, the liquid-filled PCF has a total length of about 9 mm, as shown in Figs. 1(c) and 1(d). Finally, the open end of the liquid-filled PCF was spliced with another standard SMF. It is more difficult to splice a liquid-filled PCF, rather than an unfilled PCF, with a standard SMF. When the optimized splicing parameters (prefusion power, standard −15 bit; prefusion time, 240 ms; overlap, 10 μm; fusion power one, standard −10 bit; fusion time one, 200 ms) were employed, the splice loss between the liquid-filled PCF and the SMF was reduced to about 3 dB. The repeated arc discharge technique is usually used to reduce the splicing loss of an unfilled PCF. However, only one arc discharge was done to splice the liquid-filled PCF in our experiment, as shown in Fig. 1(e). The reason for this is that repeated arc discharges could induce gasification of the liquid material, resulting in a bubble in the splicing joint and thus a large splicing loss.

A supercontinuum white-light source (NKT SuperK Compact) and an optical spectrum analyzer (YOKOGAWA AQ6370C) were employed to measure the transmission spectrum of the liquid-filled PCF. As shown in Fig. 1(b), five bandgaps occurred within the wavelength range from 800 to 1700 nm. In other words, the index-guided PCF was transferred into a bandgap-guided PBF, resulting from the higher effective refractive index of the liquid rods in the cladding than that of the pure silica in the core. It can easy be seen in Fig. 1(b) that the extinction ratio of each bandgap is more than 40 dB due to the high refractive index ($n = 1.700$) of the filled liquid. Hence, such a liquid-filled PCF could be used to develop a promising in-fiber bandpass filter with a large extinction ratio of more than 40 dB and a low insertion loss of about 3 dB. And this filter has a compact size, because the length of the liquid-filled PCF is 9 mm.

Our experimental results show that the optical properties, i.e., extinction ratio and wavelength of the bandgaps, of the liquid-filled PCF depend strongly on the type of PCF employed, the length of the filled PCF, and the refractive index of the filled liquid. Provided a liquid with a lower refractive index is employed, a longer PCF has to be filled to increase the extinction ratio of the bandgaps in the liquid-filled PCF. So we selected a liquid with a very high refractive index of 1.700 from Cargille Labs in order to realize a compact filter based on a liquid-filled PCF as described below.

We investigated the temperature response of the liquid-filled PCF, i.e., the filter, by use of a column oven (LCO 102). The liquid-filled PCF was placed in the oven, and then temperature was raised from 30°C to 100°C. As shown in Fig. 2(a), the bandgaps shifted toward a shorter wavelength, a so-called blueshift, with the rise in temperature, resulting from the thermo-optic effect of the filled liquid, but the extinction ratio of each bandgap remained steady at a value of more than 40 dB due to the higher refractive index ($n = 1.700$) of the liquid employed. This is deferent from the phenomenon reported in [11], in which a liquid with a lower refractive index of 1.480 was employed so that the extinction ratio of the bandgap in the liquid-filled PCF reduced with the rise in temperature.

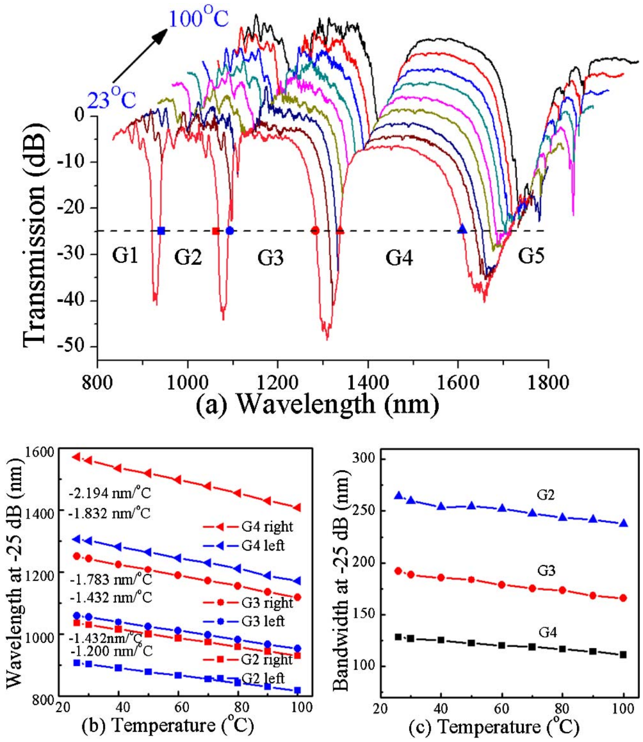

Fig. 2. (a) Transmission spectrum evolution of the liquid-filled PCF with the rise in temperature from 30°C to 100°C with steps of 10°C, (b) wavelengths, corresponding to a transmission of −25 dB, at the left and right edges of the three bandgaps, i.e., G2, G3, and G4, and (c) bandwidth of each bandgap versus temperature. Note that the bandwidth in Figs. 2(c), 3(c), and 4(c) is defined as the wavelength difference between the left and right edges of each bandgap at a transmission of −25 dB.

It is very difficult, even impossible, to measure the center wavelength of each bandgap, due to the wide bandpass wavelength range. In order to evaluate quantitatively the temperature-induced shift of the bandgap edges, we illustrated the wavelengths, corresponding to −25 dB, of the left and right edges of each bandgap at different temperatures. During the temperature rise, as shown in Fig. 2(b), the left edges of G2, G3, and G4 linearly shifted toward a shorter wavelength, with high sensitivities of −1.200, −1.432, and −1.832 nm/°C, respectively, and the right edges of G2, G3, and G4 also shifted linearly toward a shorter wavelength, with high sensitivities of −1.432, −1.783, and −2.194 nm/°C, respectively. As shown in Fig. 2(c), the bandwidths of G2 (squares), G3 (circles), and G4 (triangles) hardly changed with the temperature rise. So the proposed filter based on the liquid-filled PCF is wavelength tunable, with a sensitivity of up to 2.194 nm/°C, by means of changing the temperature and has an almost constant bandwidth and a large extinction ratio of more than 40 dB within the whole wavelength tuning range of more than 100 nm.

We investigated the response of the liquid-filled PCF to the bend applied. The liquid-filled PCF was bent using the experimental setup shown in Fig. 3, as reported in [23]. An end of the fiber was fixed, and the other end was moved gradually toward the fixed end. We measured the transmission spectrum evolution of the liquid-filled PCF with the increase in the fiber curvature, as shown

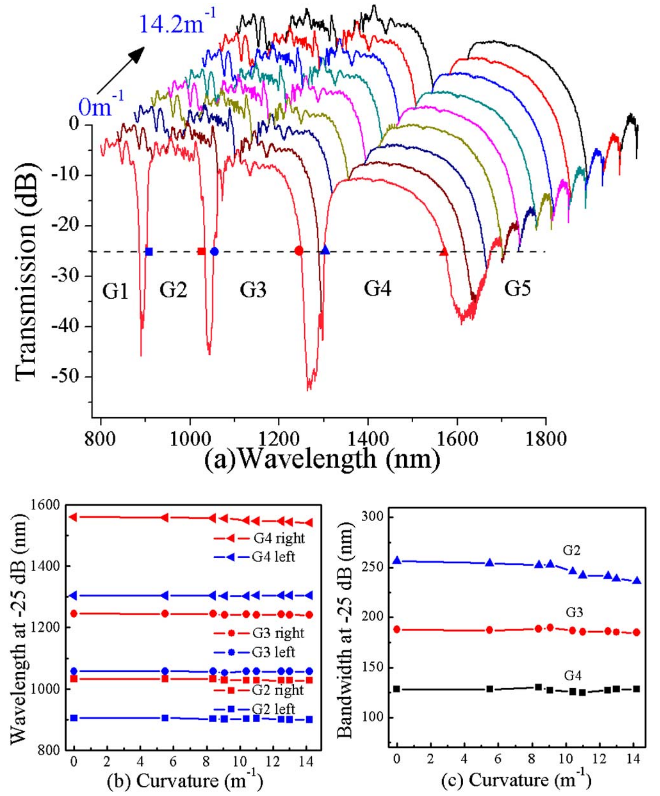

Fig. 3. (a) Transmission spectrum evolution of the liquid-filled PCF with the increase in curvature, (b) wavelengths, corresponding to a transmission of −25 dB, at the left and right edges of the three bandgaps, and (c) the bandwidth of each bandgap versus the curvature.

in Fig. 3(a). The wavelengths, corresponding to the transmission of −25 dB, at the left and right edges of the three bandgaps and the bandwidth of each bandgap are illustrated in Figs. 3(b) and 3(c) in order to evaluate quantitatively the bend-induced shift of the bandgap edges. As shown in Fig. 3, the transmission spectrum of the liquid-filled PCF hardly changed with the increase in the fiber curvature. Also, the bandgap edges and the bandwidths were insensitive to the bend. Hence, the bend of the fiber does not disturb the function of the proposed filter. However, provided a liquid with a low refractive index of 1.480 is used to fill a PCF with a longer length of 200 mm, the transmission spectrum is sensitive to the bend applied, as reported in [24]. So the function of the liquid-filled PCF could depend on the length of the filled PCF and the refractive index of the liquid employed, which will be investigated in our further research.

We investigated the response of the liquid-filled PCF to the tensile strain. An end of the fiber was fixed, and the other end was stretched by use of a translation stage. We measured the transmission spectrum evolution of the liquid-filled PCF with the increase in the tensile strain, as shown in Fig. 4(a). The wavelengths, corresponding to a transmission of −25 dB, at the left and right edges of the three bandgaps and the bandwidth of each bandgap are illustrated in Figs. 4(b) and 4(c) in order to evaluate quantitatively the stretch-induced shift of the bandgap edges. As shown in Fig. 4, the transmission spectrum of the liquid-filled PCF hardly changed with the increase in the tensile strain. Also, the bandgap edges and the bandwidths were insensitive to the stretch force. Hence, the tensile strain of the fiber does not disturb the function of the proposed filter.

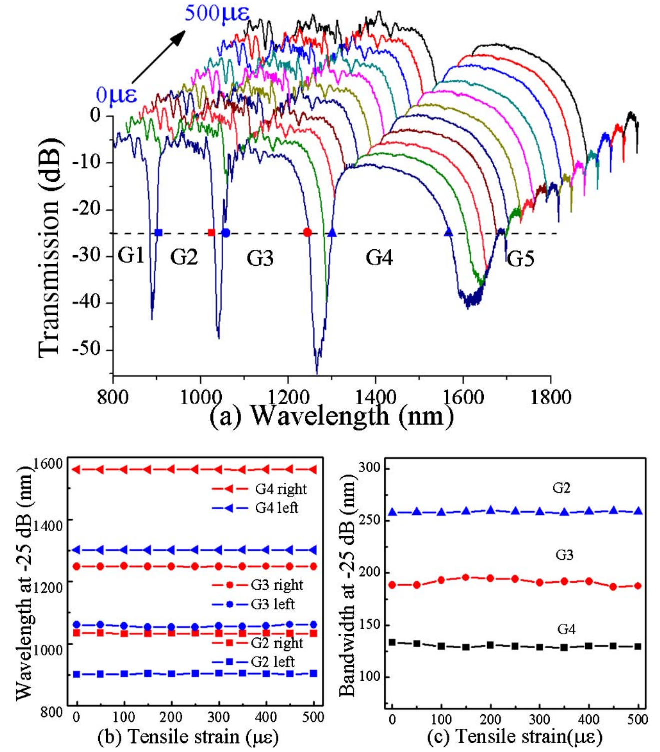

Fig. 4. (a) Transmission spectrum evolution of the liquid-filled PCF with the increase in the tensile strain from 0 to 500 με with steps of 50 με, (b) the wavelengths, corresponding to a transmission of −25 dB, at the left and right edges of the three bandgaps, and (c) the bandwidth of each bandgap versus the tensile strain.

We have fabricated five liquid-filled PCF samples with the same parameters and then investigated their response to temperature, bend, and tensile strain. The same experimental results were achieved. In other words, the bandgap of each liquid-filled PCF sample is sensitive to temperature and insensitive to bend and tensile strain, which is the advantage of our bandgap-induced filters. In contrast, the optical properties of the mode-coupling-induced filters, e.g., long-period fiber gratings, are usually sensitive to temperature, bend, and tensile strain [2,3].

A full-vectorial plane wave method [1] was used to calculate modal maps, i.e., effective index curves, for the modes guided in the liquid-filled PCF at temperatures of 23°C and 100°C, as shown in Fig. 5. Thermo-optic effects of both the filling liquid and the pure silica background were taken into consideration in the calculations. To compare with the calculated results, we also measured the transmission spectra of the liquid-filled PCF at the same temperatures. As shown in Fig. 5, the simulation results and the experimental measurements show, in general, good qualitative agreement. Moreover, five bandgaps are observed in both the calculated modal maps and the measured transmission spectra at a temperature of 23°C within the wavelength range from 800 to 1700 nm. As shown in Fig. 5(b), the bandgap, i.e., G1,

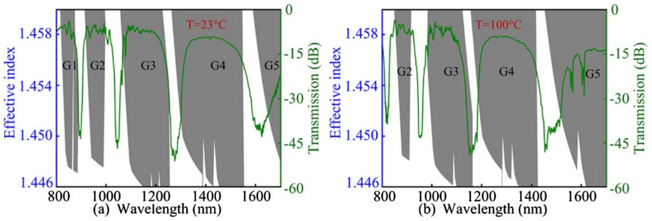

Fig. 5. Calculated bandgap maps and measured transmission spectra of the liquid-filled PCF at a temperature of (a) 23°C and (b) 100°C.

located at the shortest wavelength disappeared and another bandgap, i.e., G5, located at the longest wavelength was gradually observed at a temperature of 100°C, resulting from the blueshift of the bandgaps with the rise in temperature from 23°C to 100°C due to the negative thermo-optic coefficient of the filled liquid.

In summary, the liquid-filled PCF could be used to develop a compact tunable multibandpass filter with a short size of about 9 mm and a high wavelength tuning sensitivity of up to −2.194 nm/°C. Such a PCF-based filter maintains an almost constant bandwidth and a large extinction ratio of more than 40 dB within the whole tuning range of the wavelength. Moreover, both the tensile strain and the bend of the fiber do not disturb the function of the PCF-based filter, because the transmission spectrum of the filter is insensitive to the stretch force and the bend. Thus, our proposed filter could find wide application in all-fiber optical communication systems.

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