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Transmission Bandwidth Tunability of a Liquid-Filled Photonic Bandgap Fiber *

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A temperature tunable photonic bandgap fiber (PBGF) is demonstrated by an index-guiding photonic crystal fiber filled with high-index liquid. The temperature tunable characteristics of the fiber are experimentally and numerically investigated. Compression of transmission bandwidth of the PBGF is demonstrated by changing the temperature of part of the fiber. The tunable transmission bandwidth with a range of 250 nm is achieved by changing the temperature from 30°C to 90°C.

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Photonic crystal fibers (PCFs),[1,2] a special kind of optical fibers with air holes running along the length of the fibers, have many new characteristics compared to conventional optical fibers. The presence of air holes in PCFs has given the possibility of filling the fiber with liquids. Hence, some functional materials which have special properties could find novel and improved applications when they are brought into air-holes of PBGFs and this has opened up the possibility of creating tunable fibers and tunable fiber based devices.[3−8]

We notice that filling PCFs with materials has been intensively studied in recent years. Tunable devices based on air-silica PCFs, such as fiber filters and fiber gratings, have been proposed by filling their air-holes with active materials.[9,10] What is more, PBGFs can be implemented by filling the index-guided air-silica PCFs with high-index materials, whose bandgaps can be shifted by varying the index of the material. For instance, by filling single-core air-silica PCFs' air-holes with liquid polymer or liquid crystal (LC), tunable PBGFs and PBGF devices have been demonstrated.[3−10] Not only can the position of the bandgaps of the PBGFs be tuned but also the bandwidth of the bandgaps can be tuned.[11,12] Scolari *et al.*[11] have achieved 130 nm bandwidth tunability by changing the temperature from 30°C to 90°C based on PCF filled with two different liquid crystals. In Ref. [12], an all-in-fiber tunable bandpass filter has been demonstrated by applying a thermal gradient to a PCF filled with a high index fluid.[12] In this Letter, a tunable photonic bandgap fiber (PBGF) is firstly demonstrated by filling an index-guiding photonic crystal fiber (PCF) with high-index liquid polymer. Then we demonstrate a simple bandwidth tunable technology by changing the temperature of part of the liquid-filled PBGF. We have achieved 250 nm bandwidth tunability by changing the temperature from 30°C to 90°C. Compared with Refs. [11,12], the proposed bandwidth tunable technology has advantages of easy realization and wide tunable range.

The PCF we adopted in the experiment is presented in Fig. 1, where the pitch Λ (hole-to-hole distance) is about 6.36 μm, the average air-hole's diameter D is 3.67 μm. The air holes are arranged in a regular hexagonal pattern, and the periodic arrangement makes the PCF a good choice to achieve a liquid-filled PBGF. The PCF was fabricated by Yangtze Optical Fibre and Cable Company Ltd, China. The liquid polymer we used is certified refractive index liquid (produced by Cargille Labs), whose index is 1.5143 at 25°C, and with negative temperature coefficients $dn/dt = -0.000393°C^{-1}$.

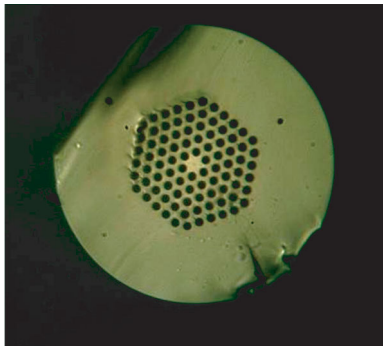


Fig. 1. Microscope image of the PCF's section structure.

First, all the air holes of the PCF were filled with the liquid, which was achieved by using a decompression device. The length of the liquid-filled PCF is about 10 cm. We measured the transmission spectrum (shown in Fig. 2) of the Liquid-filled PBGF with a fiber based supercontinuum source. In Fig. 2, the transmission spectrum of the PBGF at 30°C is recorded by a black line. The transmission spectrum in Fig. 2 presents two bandgaps. The bandwidths

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of the bandgaps are about 350 nm from 1300 nm to 1650 nm (bandgap 1) and 200 nm from 900 nm to 1100 nm (bandgap 2), respectively. The bandgap edges shown in Fig. 2 in the dashed line are calculated by the plane-wave-expansion method (PWEM).[13] The simulation matches well with the experimental results. The index-guiding PCF is transformed into a PBGF, and the two bandgaps in Fig. 2 correspond to gaps between band 6 and band 7 (bandgap 1) and between band 12 and band 13 (bandgap 2) respectively. The insertion loss for our results in this study is generally larger than 15 dB (for typical wavelengths in bandgap 1). This large insertion loss is contributed mostly to the butt splicing and mode mismatch between single-mode fibers and the PCF, which was experimentally estimated to be about 10 dB. Thus the loss of the PBGF is about 5 dB. However, by using better splicing technology and mode match fibers, we believe that the insertion loss can be significantly reduced.

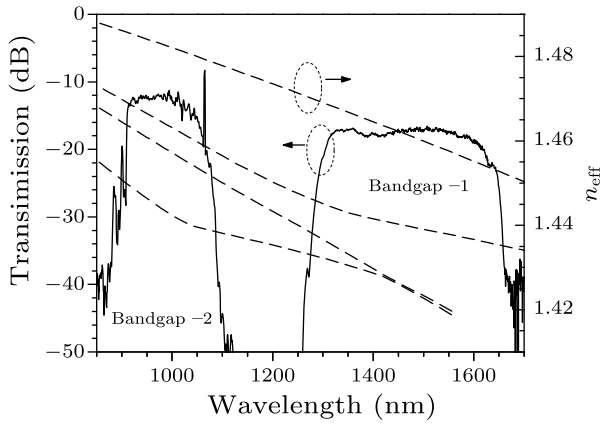


Fig. 2. Transmission spectrum of the liquid-filled PCF. The dash lines are the numerical results calculated by PWEM.

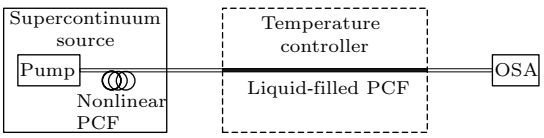


Fig. 3. Experimental setup for temperature tuning.

Then the liquid-filled PBGF is put into a temperature controller for temperature tuning. The experimental setup for temperature tuning is presented in Fig. 3. Temperature is changed from 30°C to 90°C and the transmission spectrums at the temperature of 30°C, 50°C, 70°C and 90°C are shown in Fig. 4(a). As the temperature increases, the bandgaps shift toward a short wavelength. For bandgap 1, the blue-shift speed is averaged to be 6 nm/°C and for bandgap 2, the blue-shift speed is averaged to be 3 nm/°C, as shown in Fig. 4(a). When temperature rises to 90°C, bandgap-1 bandwidth is about 300 nm from 920 nm to 1220 nm, which means a blue-shift of about 400 nm and a compression of about 50 nm compared with that under temperature of 30°C. For the liquid we adopted in this study, changing the temperature leads to a large change of the refractive index for the liquid ($dn/dt = -0.000393°C^{-1}$). Therefore, the drop of the liquid's refractive index, which is resulted from rising temperature, will decrease the index contrast between the liquid and silica. According to the ARROW regime described by Litchinitser *et al.*,[14] the transmission spectrum of the PBG structure is largely determined by the index contrast: when the index contrast decreases, there are obvious blue-shift of bandgaps and compression of the bandgaps' width, as seen in Fig. 4(a). The numerical results calculated by PWEM have also been demonstrated, which are shown in Fig. 4(b). The shifts and the decrease of the bandgaps can also be found in the simulation results, which is in good agreement with the experiment.

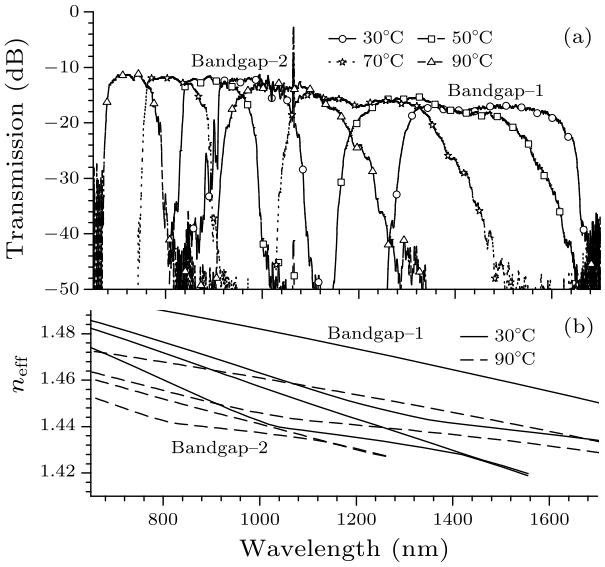


Fig. 4. (a) Rise of temperature changes the bandgap of the liquid-filled PCF. (b) Simulation of the bandgaps of the liquid-filled PCF at different temperature.

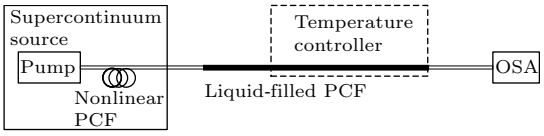


Fig. 5. Schematic illustration of the setup for bandwidth tuning.

In order to achieve a wider range of tunable transmission bandwidth of the PBGF, We put part of the liquid-filled PBGF in the temperature controller and the residual part is outside of the temperature controller, as shown in Fig. 5. The transmission spectrum is the overlap of the two parts of the PBGF. The bandgaps of the heated part of the PBGF move towards short wavelength, but the bandgaps of the unheated part of the PBGF outside the temperature controller are fixed. Consequently, the overlap of the

two parts is narrowed. The transmission spectra of the PBGF for different temperatures are shown in Fig. 6. Figure 6(a) shows the changes of bandgap 1. Figure 6(b) shows the changes of bandgap 2. Bandgap 1 is compressed from about 350 nm to about 100 nm from 30°C to 90°C. A tunable transmission bandwidth with a range of 250 nm is achieved by changing the temperature of bandgap 1 from 30°C to 90°C. Bandgap 2 at 30°C does not overlap bandgap 2 at 90°C, which makes bandgap 2 vanish at 90°C. These processes are reversible, which means that the bandwidth of the bandgaps will be wider when the temperature rises. These allow the fabrication of a tunable switch or a tunable passband filter.

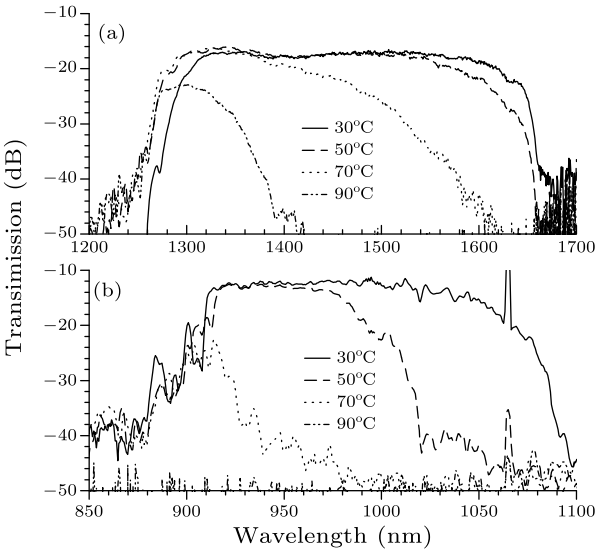


Fig. 6. (a) Compression of bandgap 1 at different temperatures. (b) Compression of bandgap 2 at different temperatures.

In conclusion, we have experimentally demonstrated a liquid-filled PBGF by filling a PCF with a temperature-responsive liquid. The experimental and numerical investigations indicate that transmission spectrum of the liquid-filled PBGF is temperature tunable. The bandgaps of the liquid-filled photonic crystal fiber can be changed by adjusting temperature: compression of bandwidth and blueshift. Furthermore, we have demonstrated temperature tunable compression for bandgaps, which can be used as a continuously tunable passband filter by changing the temperature of some section of the fiber. This filter offers flexible bandwidth tunability. In particular, 250 nm bandwidth tunability is achieved in the temperature range from 30°C to 90°C. The proposed method to achieve the temperature tunable bandwidth has advantages of easy realization and wide tunable range. Considering the large number of PCFs and available temperature tunable liquids, we can choose the wavelength and the tunability as we want. We believe that temperature tunable devices based on the liquid-filled PBGFs can be a promising candidate for applications as fiber sensors and optical communication devices.

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