Front. Optoelectron. China 2010, 3(3): 289–291
DOI 10.1007/s12200-010-0100-2

RESEARCH ARTICLE

Deep notch filter based on liquid-filled photonic crystal fiber

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Abstract A deep notch filter in a liquid-filled photonic bandgap fiber (PBGF) realized via filling an erbium-doped solid core photonic crystal fiber with high-index liquid is proposed and demonstrated. The numerical investigation indicates that the notch is formed due to avoid-crossing effect between the fundamental mode and LP_{02} supermodes. The resonance wavelength of the filter can be tuned by adjusting the temperature of the liquid-filled PBGF and shifts toward short wavelength. The blue-shift speed average is 1.3 nm/°C.

Keywords photonic crystal fiber, liquid-filled, photonic bandgap fiber, filter

1 Introduction

Photonic crystal fibers (PCFs) [1], 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 [1–3]. PCFs can be commonly classified as index-guiding PCFs, which guide light through total internal reflection (TIR) and photonic bandgap fibers (PBGFs), which guide light in a low-index core through the photonic bandgap (PBG) effect. The presence of air holes in PCFs has been given the possibility of filling the fiber with liquids [4–6].

By filling a TIR-PCF with liquid having a higher refractive index than silica, a PBGF is created [4]. Such a fiber guides light owing to multiple reflections from the high-index liquid and silica interfaces, and transmits light only over certain wavelength ranges corresponding to the bandgaps of the cladding. As these ranges depend on the refractive index of the liquid in the holes of the PCF, such PBGF can have their properties adjusted after fabrication, by changing the liquid inside the PCFs, by thermally tuning the refractive index of the liquid [4], or by using electrical tuning [7,8]. This has opened up the possibility of creating tunable fibers and tunable fiber based devices.

Recently, deep notch filters have been realized in liquid-filled PBGFs by inducing a mechanical long-period grating in the fiber [9]. Such a grating results in a coupling of the fundamental core mode to higher order modes of the fiber core or cladding. These higher order modes have a high loss, and deep notches in the transmission windows of the fiber are realized. Recently, Noordegraaf et al. demonstrated a deep notch filter in PBGFs without using gratings but simply by exploiting the properties of the liquid crystal and the fiber to create a loss in a narrow wavelength band [10]. In this paper, a deep notch filter in PBGFs is demonstrated by filling high-index liquid into an erbium-doped PCFs, and the producing mechanism is investigated and revealed using numerical simulations. The theoretical results agree with the experimental results well.

2 Experiment and results

The PCF adopted in the experiment is presented in Fig. 1, where the pitch (hole-to-hole distance) is about 4.20 μm,

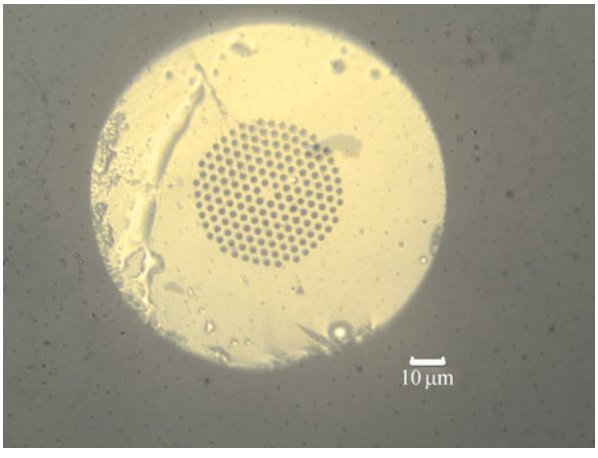


Fig. 1 Microscope image of erbium-doped PCF's section structure

Received April 16, 2010; accepted May 3, 2010

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and the average air-hole's diameter is about 2.35 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 diameter of the erbium-doped core, whose index is higher than silica, is about 4.20 μm. The liquid we used is certified refractive index liquid Series B16500 (produced by Cargille Labs), whose index is 1.650 at 25°C, and with negative temperature coefficients $dn/dt = -0.000393°C^{-1}$.

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 8 cm. The two ends of the liquid-filled PCF were coupled with standard single mode fiber. We measured the transmission spectrum (shown in Fig. 2) of the liquid-filled PBGF with a supercontinuum source and an optical spectrum analyzer. In Fig. 2, the transmission spectrum presents two bandgaps. There is a deep notch with center wavelength at 1132 nm, whose 3 dB width is 18 cm, in the left bandgap. The insertion loss for the liquid-filled PBGF is generally larger than 10 dB.

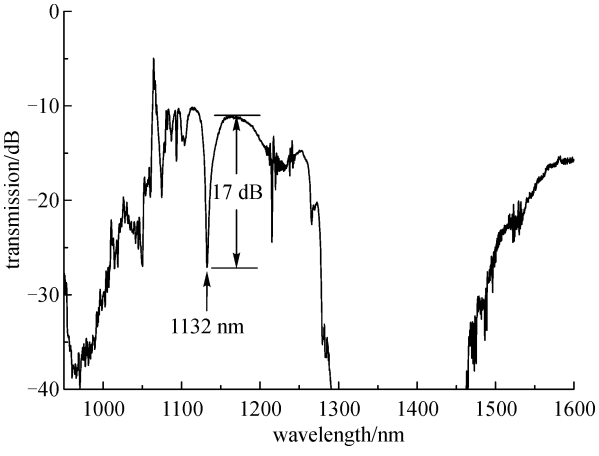


Fig. 2 Transmission spectrum of liquid-filled PCF

Then, the liquid-filled PBGF is put into a temperature controller for temperature tuning. The transmission spectra at different temperatures are shown in Fig. 3. As the temperature increases, the loss dip moves toward shorter wavelength. The blue-shift speed is averaged to be 1.3 nm/°C. The shift can be explained by the refractive index of the liquid as a function of temperature. Therefore, the drop of the liquid's refractive index, which resulted from rising temperature, will make the loss dip move toward shorter wavelength. This can be used as a tunable filter or temperature sensor.

3 Numerical simulation

The bandgap of the liquid-filled PBGF is calculated by the

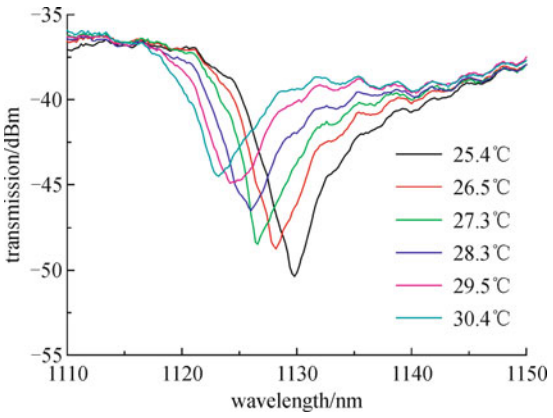


Fig. 3 Rise of temperature changes position of notch

plane-wave-expansion method (PWEM) [11]. Figure 4 shows the calculated results, and it matches the experimental spectrum well. The two bandgaps in Fig. 4 correspond to gaps between band 6 and band 7 (bandgap-1) and between band 12 and band 13 (bandgap-2), respectively.

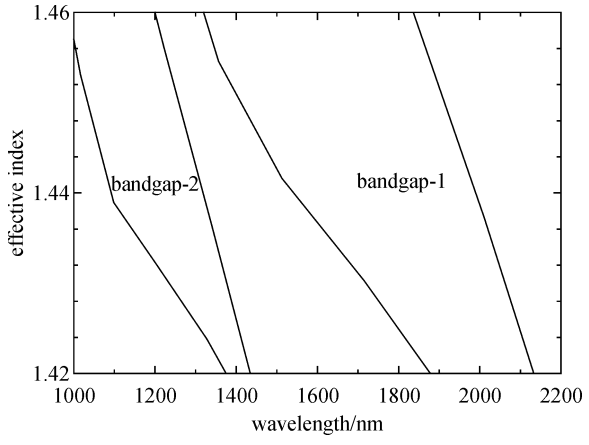


Fig. 4 Numerical result of bandgaps of liquid-filled PBGF

In bandgap-2, we use finite element method (FEM) [12] to calculate the fundamental mode dispersion curve. Figure 5 shows the mode dispersion curve at the wavelengths around the notch occurring. The high-index erbium-doped core increases the effective index of the fundamental mode of the PCF, which makes avoid-crossing happen around 1130 nm. The insets in Fig. 5 are the mode fields of different points on the line. From these figures, we can see avoid-crossing between the fundamental core mode and the LP_{02} supermode, which brings the loss dip.

We also calculated the avoid-crossing at different temperature. The result is shown in Fig. 6. The resonant wavelength of the notch shifts toward shorter wavelength; the temperature increase can also be found in the simulation results, which is in good agreement with the experiment.

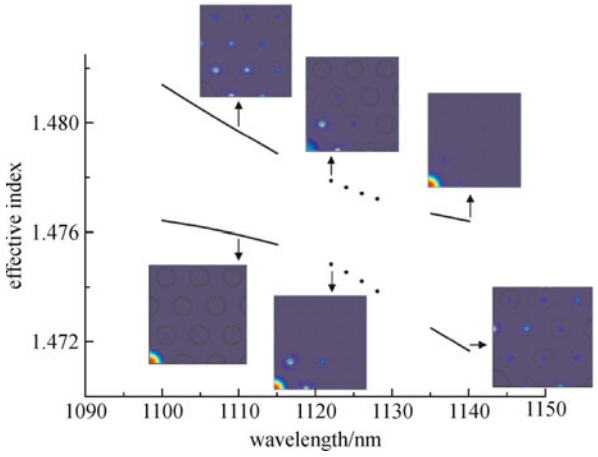


Fig. 5 Simulated results of avoid-crossing

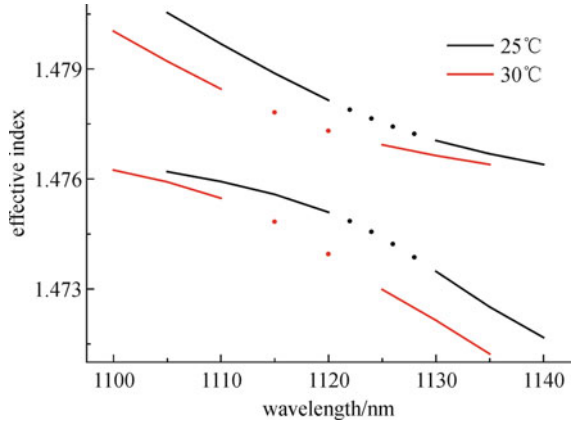


Fig. 6 Simulation of avoid-crossing at different temperature

4 Conclusions

We have experimentally demonstrated a deep notch in a liquid-filled PBGF by filling an erbium-doped PCF with high-index liquid. The numerical investigation indicates that the notch is formed due to the avoid-crossing effect between the fundamental mode and LP_{02} supermodes. The resonant wavelength of the notch can be changed by adjusting the temperature of the liquid-filled PBGF, it shifts toward shorter wavelength, and the blue-shift speed is average to be 1.3 nm/°C. This can be used as a tunable filter or sensor. Considering the large number of PCFs and available liquids, we can choose the wavelength, and the tunability as we want was based on the same operation principle.

Acknowledgements This work was supported by the National Key Basic Research and Development Program of China (No. 2010CB327605), the National Natural Science Foundation of China (Grant Nos. 50802044, 10774077, and 60736039), and the Doctoral Fund of Ministry of Education of China (No. 200800551025).

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