Highly Sensitive Temperature Sensor Based on Hybrid Photonic Crystal Fiber

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Abstract: A hybrid guiding mechanism in photonic crystal fiber (PCF) is realized by selectively infiltrating liquid crystal 5CB into a twin-core PCF. Due to the introduction of PBG guiding mechanism into the index-guiding twin-core PCF, the hybrid PCF shows strong temperature responsiveness and thus possesses good potential for sensing applications.
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1. Introduction

Since it is firstly demonstrated in the year of 1992 by P. Russel [1] and S. John [2], photonic crystal fiber (PCFs) with air holes running along their length have been intensively explored in an effort to understand their broad potential [3]. In general, a PCF guides light either by total internal reflection (TIR) or photonic bandgap (PBG) mechanisms, dependent on the fiber structure [4]. Although the physical structure of a PCF is fixed once it is fabricated, control of the transverse patterning in PCF by selectively infiltrating liquid into air holes allows for precise tailoring the properties of the guided modes [5]. Base on this idea, researchers have constructed various based optical devices such as directional couplers [6, 7] and sensors [8] *etc* by selectively infiltrating diverse liquid into one or two air holes of a PCF. In these schemes, air hole infiltrated by functional liquid can form a new TIR circular waveguide due to the refractive index (RI) contrast between the liquid and the background [6]. The silica core and liquid core co-existing in the PCF are capable of coupling with each other in the condition of phase matching. However, chromatic dispersion prevents phase matching in the desirable case when both silica core and liquid core are in fundamental modes [9]. For this reason, phase matching between fundamental mode of the silica core and high-order modes of the liquid core has been used for intercoupling or mutual interference. Nevertheless, high-order modes usually have much lower intensities than the fundamental mode, resulting in either a limited coupling efficiency or a relatively low finger contrast in interference spectrum according to the coupled mode theory [9]. This shortage would deteriorate operation performance of the devices based on liquid infiltrated PCF.

On the other hand, TIR type PCF can be converted into PBG mechanism guiding PCF by filling air holes with high RI liquid [10], offering us an alternate solution to tailor the property of PCF. Recently, *Xiwen Sun* proposed a novel class of PCF with a hybrid light guiding mechanism by selectively infiltrating high RI material into the first ring of air holes around one of silica cores in a dual-core PCF [11]. In this way, a bandstop or bandpass filter allowing highly accurate control of filtering wavelength can be easily implemented. Yet, only simulation results are presented in the above work.

In this paper, we theoretically and experimentally explore a hybrid PCF by infiltrating liquid crystal into a twin-core PCF. Both the index guiding and photonic bandgap guiding mechanism exist in the fiber, leading to interesting properties for sensing applications. A finite element method (FEM) is employed to simulate the mode properties of the liquid crystal infiltrated hybrid PCF. Temperature response of the liquid crystal infiltrated hybrid PCF is also experimentally studied.

2. Working principles and simulations

A twin-core PCF (TCPCF) made of pure silica is considered for the study, as shown in Fig. 1(a). In the TCPCF with triangular lattice of air holes, two solid cores are formed by replacing two air holes with two pure silica rods. Diameter and pitch of air holes are around d=2.3μm and Λ=4μm respectively, and the outer diameter of the PCF is 125μm. Liquid crystal adopted in this work is 4-pentyl-4'-cyanobiphenyl (5CB), a type of nematic liquid crystalline material with rod-like molecules [12]. 5CB has a large optical birefringence defined as a difference between extraordinary RI (n_e) and ordinary RI (n_o), with their chromatic dispersion curves shown in Fig. 1(b). The spectral dependences of RIs are obtained by three-coefficients Cauchy model. In general, RI of liquid crystal shows strong temperature dependence. For liquid crystal 5CB adopted in this work, the clearing temperature T_c is 34.6 ºC [12], after which, 5CB turns from anisotropic phase into isotropic phase.

The designed hybrid PCF structure is illustrated in Fig. 1(a), which is realized by selectively infiltrating 5CB into the first ring of air holes surrounding one of silica cores in the TCPCF. In the modified TCPCF structure, the left silica core has a higher RI than the air holes cladding, so that light is guided by TIR mechanism. While in the right core, since RI of the silica core is lower than that of the liquid crystalline cladding, PBG mechanism dominates the light guiding. Therefore, two different types of light-guiding mechanism co-exist in the modified TCPCF. Due to different light mechanisms and RI profiles of the two parallel waveguides, mode mismatch between the two cores is usually large, causing light propagate independently in each core. However, high RI of 5CB can impose phase matching between the two parallel waveguides at a particular wavelength, at which the propagation constants of the two cores are equal, and coupling between the two cores happens over a narrow wavelength range.

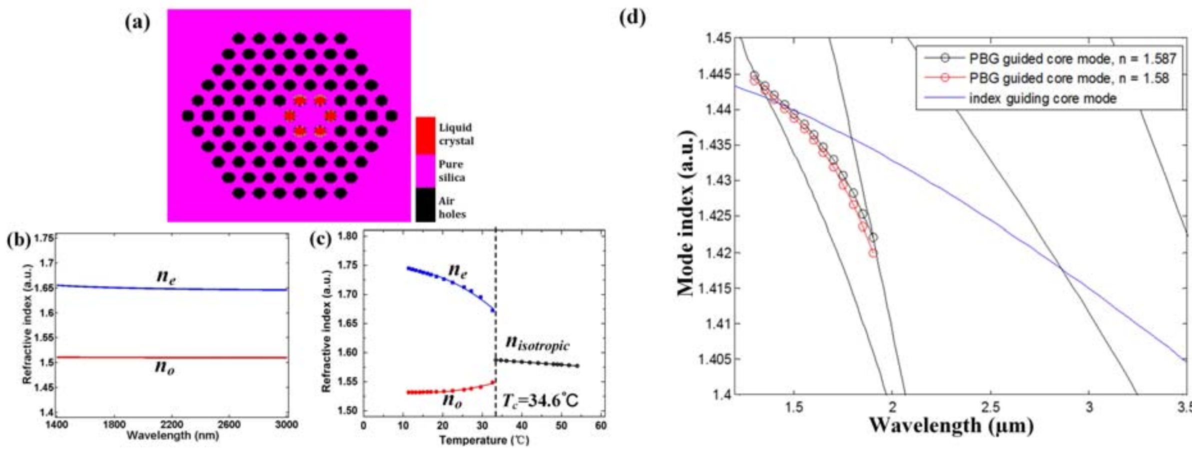

Fig. 1. (a) Refractive index (RI) profile of the liquid crystal filled twin core PCF; (b) Dispersion curve of 5CB; (c) Temperature dependence of RI of 5CB; (d) Mode dispersion curves of the two cores in the hybrid PCF.

The guiding properties of the hybrid PCF structure can be understood from the dispersion curves presented in Fig. 1(d). According to coupled mode theory, optical modes of each core in the hybrid PCF structure will be perturbed by the other one [11]. Therefore, we firstly calculate the effective RI of mode of TIR guiding core and that of PBG guiding core separately. In Fig. 1(d), when the dispersive curve of the 5CB infiltrating PCF interacts with that of a noninfiltrating PCF, crossing occurs, propagation constants of the two modes are matched. At phase matching conditions, the couplings between two cores result in power transfer back and forth as light propagates along the fiber length. Then, the bandpass filtering can be achieved.

3. Experimental results and discussion

In the experiment a 5CB-infiltrated hybrid PCF is carefully prepared by using UV glue (NOA81, Thorlabs Inc.) to block the air holes and leaving the desirable air holes surrounding one core untouched. The microscope images of fabricated samples are presented in Fig. 2(b), where the blur gray area shows the air holes infiltrated with 5CB, the black circular spots show the un-infiltrated air holes, and the light gray area represents pure silica. Length of the fabricated hybrid PCF structure is about 5 cm. After fabrication, both sides of the PCF are spliced to single mode fiber (SMF) using a fusion arc splicer (Fujikura, FSM-100P+). By controlling the splicing parameters, a neat splicing point without bubble and collapsing can be obtained, as illustrated in Fig. 2 (c). For temperature response characterization, the hybrid PCF sample is placed in a temperature controller. Then the SMF ends are connected to a broadband source and optical spectrum analyzer, as shown in Fig. 2(d).

Transmission spectra of the hybrid PCF under different temperature are presented in Fig. 2. It can be seen from Figs. 2(e) and 2(g) that when the temperature is below the clearing temperature of 5CB, transmission spectrum shifts to longer wavelength, while it shifts to short wavelength as the temperature surpassing the clearing temperature. Specifically, when the temperature is below the clearing temperature, i.e. 5CB is under the nematic condition, the temperature sensitivity in the heating process is about 4.62nm/°C, while the temperature sensitivity in the cooling process is about 4.75nm/°C, as shown in Fig. 2(f). The existence of hysteresis may be attributed to thermal expansion of 5CB, which after cooling the liquid crystal does not return to the same state. When the temperature is higher than the clearing temperature, i.e. 5CB is under isotropic condition, the temperature sensitivity is measured as -3.43nm/°C, as illustrated in Fig. 2(h). The inverse resonant wavelength shift is because of the different dependences of RI of 5CB on the temperature when it is below and surpassing clearing temperature, as can be understood from Fig. 1(c).

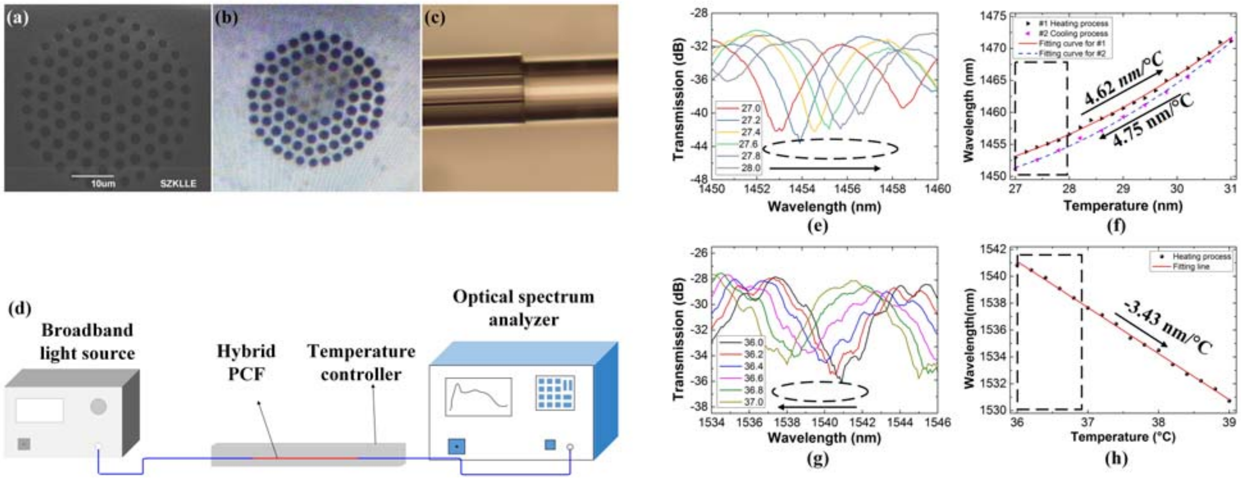

Fig. 2. Fabrication and Experiment. (a) Scanning electron microscope picture of the TCPCF employed in this work; (b) Microscope picture of infiltrated PCF; (c) Detailed view of the splicing point between the PCF and SMF, showing that no bubble is formed during the splicing process; (d) Experimental setup for characterizing temperature response of the hybrid PCF; (e) Transmission spectra under different temperature for the nematic liquid crystal condition; (f) Dependency of resonant wavelength on the temperature when 5CB is under the nematic condition; (g) Transmission spectra under different temperature for the isotropic liquid condition; (h) Dependency of resonant wavelength on the temperature when 5CB is under the isotropic condition.

4. Conclusion

A highly sensitive temperature sensor based on a hybrid PCF is experimentally demonstrated in this work. The hybrid PCF is formed by selectively infiltrating liquid crystal 5CB into the first ring of air holes surrounding one of silica cores in the TCPCF. FEM is employed to simulate the mode dispersion curves of the 5CB infiltrated hybrid PCF. Temperature response of the 5CB infiltrated hybrid PCF is also studied. Experimental results show that the temperature sensitivity can be as high as 4.75nm/°C when the temperature is below clearing temperature of 5CB, while is -3.43nm/°C as the temperature surpassing clearing temperature. In future work, the coupling characteristic of the hybrid PCF and the potential usage as a temperature-tunable wavelength filter will be thoroughly investigated.

5. References

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