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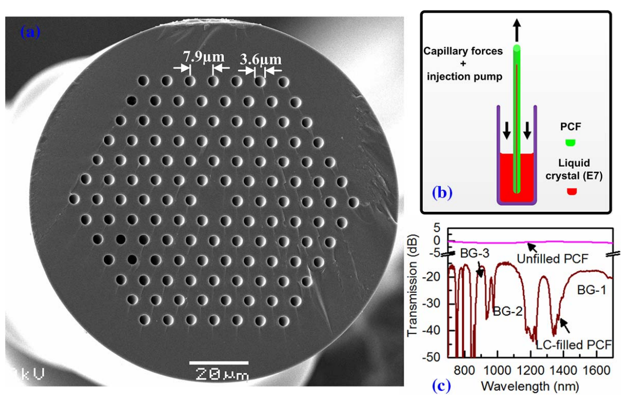

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Broadband Thermo-Optic Switching Effect Based on Liquid Crystal Infiltrated Photonic Crystal Fibers

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Abstract: We demonstrate a liquid-crystal-filled photonic crystal fiber (PCF) and investigate its temperature response with a unique liquid crystal (LC) clearing point of 58 °C. Opposite temperature responses are observed at the temperature that is lower and higher than the LC's clearing point, respectively. Such a LC-filled PCF could be used to develop a promising optical switch with a broadband operation range of 102.5 nm via a small temperature change of less than 1.5 °C. Moreover, the LC-filled PCF exhibited an ultrahigh temperature sensitivity of 105 nm/°C and could find potential applications in the field of temperature sensors.

Index Terms: Optical switching, photonic crystal fiber, liquid crystal, temperature.

1. Introduction

Solid-core photonic crystal fibers (PCFs) comprise a silica cladding with a periodic array of air-holes running down the entire length of the fiber [1]. As a result, PCFs can provide a flexible platform for infiltrating the air holes with various advanced materials [2]–[6]. Such fluid-filled solid-core PCFs can have their properties adjusted by thermally tuning the refractive index of the fluid [7] or by magnetic tuning [6] or, when the fluid used is a liquid crystal [8], by using electrical field tuning. On the other hand, fluid-filled solid-core PCFs can be developed to innovative photonic devices such as switches [9]–[14], polarization beam splitters [15], and rotators [16]. Wang *et al.* report a thermo-optic switching effect with a high extinction ratio of 30 dB by means

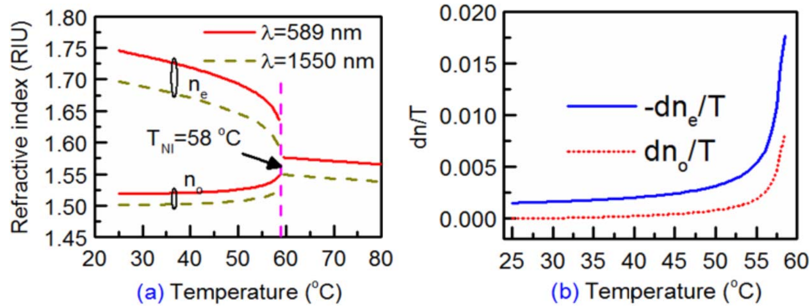

Fig. 1. (a) Temperature dependence of the refractive index of the nematic liquid crystal (E7, Merck, http://www.merck.com). (b) The calculated dn_o/dT and dn_e/dT for E7 at the wavelength of 1550 nm.

of filling a fluid into air holes of a solid-core PCF. However, a wide temperature adjustment of ± 10 °C can be involved owing to the liquid employed [12].

Liquid crystal (LC) is almost exclusively thermotropic, where transition between different LC states-termed mesophases takes place within certain concentration ranges. In this regards, LC is recognized to be a good infusion candidate for realizing tunable photonic crystal fiber (LC-PCF) devices. By filling LC in all holes of the fiber, the guiding mechanism of PCF from modified total internal reflection to photonic bandgap (PBG) guidance can be implemented. As a result, the PBG properties can be controlled and utilized for sensing purposes [17]–[23]. Alkeskjold *et al.* [19] demonstrated a highly temperature tuning as large as 27 nm/°C by utilizing a three-rod core PCF and a specially synthesized LC. Larsen *et al.* [8] proposed a thermo-optic switch based on that the PBG transmission could be totally depressed around the LC's clearing temperature.

In this letter, we investigate experimentally a thermo-optic switching effect in an index-guiding PCF filled by a liquid crystal with high refractive index, where the index-guiding PCF is transformed into a bandgap-guided photonic bandgap fiber. Fortunately, a well-known commercial mixture liquid crystal, i.e., E7, with a clearing point T_{NI} of 58 °C, was used to enhance the switching effect of a LC-filled PCF. Around the clearing point, T_{NI}, of 58 °C, E7 presents a phase transition property, namely reversible transformation between anisotropy and isotropy. More importantly, the refractive indices of the liquid crystal employed change dramatically within a short temperature range around the clearing point. As a result, the sudden refractive indices change could induce a huge bandgap shift. Such an operation could be used to develop an in-fiber broadband optical switch with a high extinction ratio of more than 30 dB by means of changing a small temperature range of less than 1.5 °C.

2. Experimental Details

As shown in Fig. 1(a), E7 has a clearing point, T_{NI}, of 58 °C indicated by the vertical dashed line. Anisotropic optical properties of E7 are described by extraordinary and ordinary refractive index of n_e and n_o. In the nematic phase, as temperature increases, n_o increases and ne decreases. The thermo-optic coefficient of both indices, between 10^{-4} and 10^{-3} RIU/°C, is comparable to isotropic optical liquids for temperatures above the clearing point, T_{NI}. In this case, the thermo-optic tuning of LC compounds serves more as an extra degree of freedom to tune the response of the LC-filled PCF. As seen from Fig. 1(b), a thermo-optic switch can be pronounced when operating close to T_{NI} by exploiting the huge increased gradient dn/dT, where material properties change dramatically within a short temperature range. It should be noted that the flow process of E7 induces dominating molecular orientation along the fiber axis, n_o takes dominating effect in modifying the wave-guiding properties of the PCF [18], [19], [24]. As for n_o, its temperature response can be described by using a four-parameter model [25], where the exponent β is a material constant, and T_{NI} is the clearing temperature of the LC material

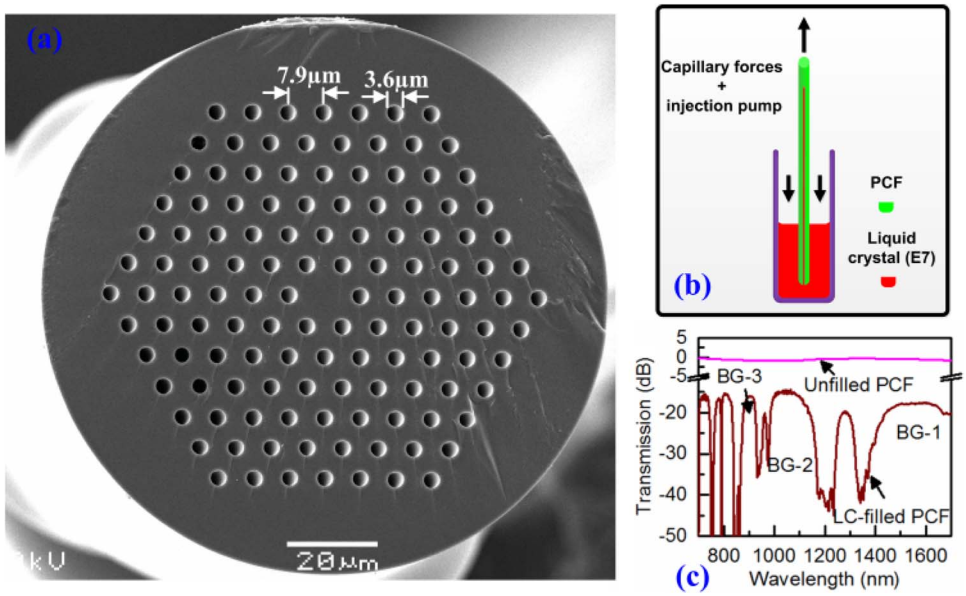

Fig. 2. (a) Cross-sectional SEM images of the PCF employed. (b) Schematic diagram for filling a liquid crystal into a PCF. (c) Transmission spectra of the LC-filled PCF.

under investigation and the fitting parameters $[A, B, (\Delta n_o), \beta]$ are [1.7546, 5.36×10^{-4}, 0.3768 0.2391]

$$n_o = A - BT - \frac{\Delta n_o}{3}\left(1 - \frac{T}{T_{NI}}\right)^{\beta} \tag{1}$$

$$\frac{dn_o}{dT} = -B + \frac{\Delta n_o \beta}{3T_c}\left(1 - \frac{T}{T_{NI}}\right)^{\beta - 1}. \tag{2}$$

In fact, the relative permittivity tensor ε_r of the liquid crystal, i.e., E7, is calculated using n_e, n_o and the rotation angle ϕ of the director n of the liquid crystal, i.e., E7, shown in Fig. 1, as follows:

$$\varepsilon_r = \begin{pmatrix} n_o^2 \sin^2\phi + n_e^2 \cos^2\phi & (n_e^2 - n_o^2)\cos\phi \sin\phi & 0 \\ (n_e^2 - n_o^2)\cos\phi \sin\phi & n_o^2 \cos^2\phi + n_e^2 \sin^2\phi & 0 \\ 0 & 0 & n_o^2 \end{pmatrix} \tag{3}$$

ϕ is the angle related to the liquid crystal's axis, and $n = (\cos\phi \ \sin\phi)$ is the director of the liquid crystal, i.e., E7.

A large mode area PCF (ESM-12, http://www.nktphotonics.com) was employed to investigate the temperature responses of the LC-filled PCF. Air holes of the PCF with a core diameter of 9 μm have an average diameter of 3.6 μm and are arranged in a hexagonal pattern with an average pitch of 7.9 μm, which are concluded from the inset of Fig. 2(a). In our experiment, one end of the PCF with a length of 150 mm was sealed in a pressure tube connected to an injection syringe, and the other end of the PCF was immerged in a bottle holding for E7 [see Fig. 2(b)]. The injection syringe was fixed on an electrically controlled moving stage to produce a uniform pressure difference. When pulling the plunger of the injection syringe, it produces a vacuum pressure in the tube. And the injection syringe would attract the liquid crystal fill into the PCF. It should be noted that the filling speed also depends on the material properties of the fluid, such as its density and viscosity. In this experiment, the pulling distance is set to 50 mm, it takes 1 hour for E7 to fill the entire length of the 150 mm long PCF.

TABLE 1

Optimized splicing parameters for a commercial fusion splicer (Fujikura-80s)

Parameters	Units	Values
prefusion power	bit	standard-25
Prefusion time	ms	180
overlap	μm	6
fusion power	bit	standard-30
Fusion time	ms	300
offset	μm	-30

Through our experimental studies, the splice between single mode fiber (SMF) and the fully liquid-filled PCF is difficult with standard arc discharge, since the oil boiling and evaporating always emerge under ultrahigh temperature during fusion splicing, which eventually results in bad physical strength and great splice losses. In [26], liquid petroleum gas flame was taken advantage of to gasify a few millimeters in length from the end of liquid-filled PCF. However, the refractive index of index-matched oil used was $n = 1.38$, which could be gasified easily. Therefore, it is extremely difficult to gasify the liquid out of the end of liquid-filled PCF with high refractive index due to its higher viscosity. Because the LC we used was with $n_o = 1.5216$ and $n_e = 1.7462$, which lead to the difficulty of splicing with SMF. The finally optimized splicing parameters for a commercial fusion splicer are shown in Table 1. For our fiber device, the main origin of the insertion loss consists of two couplings between an index guiding mode and PBG guiding mode at the first splice and between the filled and unfilled sections of the PCF, two splicing joints losses (about 3.5 dB) at the input/output and absorption loss of the liquid crystal in the holes.

Fig. 2(c) illustrates the measured transmission spectra of the LC-filled PCF at temperatures of 30 °C, three clear attenuation gaps were observed within the wavelength range from 880 to 920 nm (BG-3), from 1000 to 1170 nm (BG-2), and from 1480 to 1650 nm (BG-1), respectively. The narrow BG around 960 and 1250 nm appeared due to the anisotropic splitting of the TE_{02} and TM_{02} mode and splitting of the HE_{12} and EH_{11} mode, respectively. It's obvious that, the index-guided PCF is transferred into a bandgap-guided photonic bandgap fiber, resulting from higher effective refractive index of the liquid crystal rods in the cladding than that of pure silica in the core. It can easy be found from Fig. 2(c) that the extinction ratio of BG-2 is more than 30 dB due to the high refractive index of the filled liquid crystal. Such high extinction ratio is enough to develop a thermo-optic switch [12]. Although we demonstrated a promising in-fiber bandpass filter with a large extinction ratio of more than 40 dB by filling the index-matched liquid with a high refractive index ($n = 1.7000$), where the large extinction ratio of more than 40 dB is attributed to small absorption loss of the index-matched liquid [7]. Therefore, a thermo-optic switch with an extinction ratio of more than 40 dB is highly possible by filling a suitable liquid crystal.

3. Results

The LC-filled PCF with 12 mm length was placed in a column oven to investigate its transmission spectra at different temperature with a supercontinuum white-light source (NKT SuperK Compact) and an optical spectrum analyzer (YOKOGAWA AQ6370C). In addition, a differential thermocouple (UNI-T UT320) was used to measure the temperature with an accuracy of 0.1 °C. Fig. 3(a) illustrates the measured transmission spectra of the LC-filled PCF at temperatures of 56.5 and 58 °C, respectively. It can be seen from Fig. 3(b) that the light power at the attenuation near 1404.5 nm was enhanced from about −85.78 dBm to about −48.68 dBm, while the temperature rose from 56.5 to 58 °C. A similar effect was observed at the attenuation near 1507.0 nm.

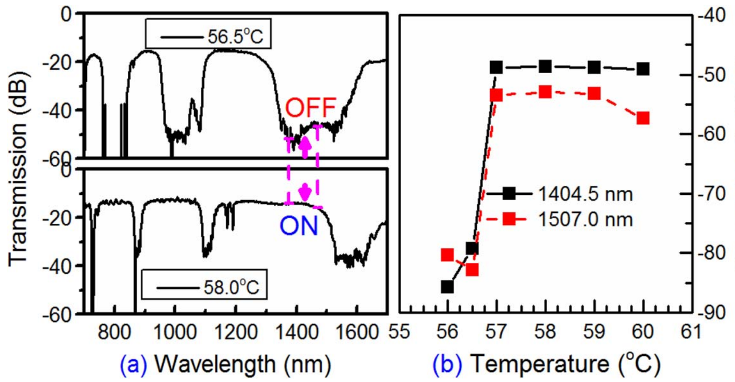

Fig. 3. (a) Measured transmission spectra of the LC-filled PCF at 56.5 and 58 °C, respectively. (b) Transmitted light powers at peak attenuations near 1404.5 and 1507.0 nm with rising temperature.

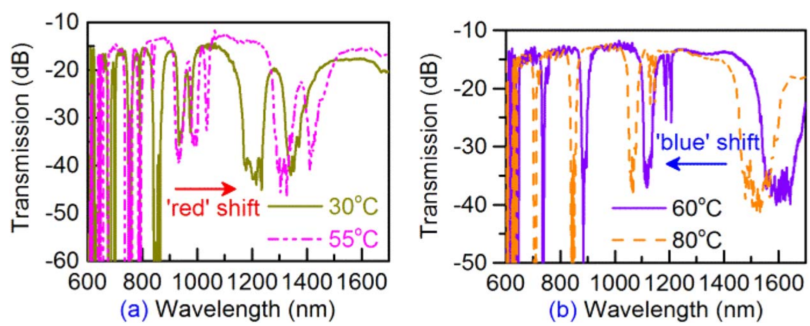

Fig. 4. Transmission spectrum evolution of the LC- filled PCF with the temperature at (a) 30 and 50 °C and (b) 60 and 80 °C.

Therefore, the LC-filled PCF could be regarded as an in-fiber optical switch that can turn ON-OFF the light transmission (from 1404.5 to 1507.0 nm) with a high extinction ratio of 30 dB via a small temperature adjustment of 1.5 °C. Although Wang *et al.* experimentally presented a thermo-optic switch with a high extinction ratio of 30 dB, the switching function was based on the absorption of the filled fluid. As a result, it operated with a wide adjustment of ±10 °C [12]. Actually electrical tuning as well as direct on-off electrical switching can present shorter response time [13], [14], but the challenge of broadband optical switching effect always exists. In addition, the performance of a thermo-optic switch based on a PCF infiltrated with a liquid crystal is investigated numerically for various fiber designs [10].

The transmission spectrum of the LC-filled PCF shifts toward a longer wavelength, so-called "red" shift, with the rising temperature from 30 to 55 °C. As the temperature approaches the clearing point of 58 °C, the temperature responses of no become very sensitive, which can be confirmed from Fig. 1(b). Moreover, we can observe totally different PBG transmission at temperature lower and higher than the temperature of 58 °C, as shown in Fig. 4. This is due to that the LC's phase has changed from anisotropic to isotropic above the temperature of 58 °C.

Fig. 5 shows that the edge wavelength shifts quickly during the process of increasing the temperature when it is lower than T_{NI} (saying $T < 58$ °C). A very slight temperature variation results in evident changes of the PBG transmission. The "red" shift sensitivity is about 105 nm/°C for the shortwave cutoff of BG-2. When it is higher than T_{NI} (saying $T > 58$ °C), LC's phase turns from anisotropy to isotropy. The linear fit method is also applied to the linear region of the curve and a sensitivity of 3.8 nm/°C is achieved. In addition, LC will return to its original state when the applied temperature is removed, this proposed sensor also showed a good repeatability.

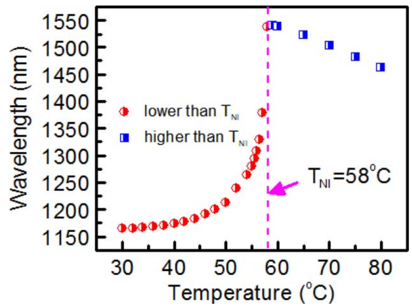

Fig. 5. Wavelengths, corresponding to a transmission of −30 dB, at the right edges of BG-2 shift versus temperature.

4. Conclusion

In conclusion, the LC-filled PCF is a BG guiding fiber, i.e., photonic bandgap fiber, at room temperature and we investigated the temperature tuning properties of a LC-filled PCF. Because of the special temperature responses of LC's indices and its phase transition property, the LC-filled PCF transmission is found to have different temperature responses at different temperature ranges, and the PBG transmissions are totally different at temperatures lower or higher than clearing point.

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