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Tunable thermo-optic switch based on fluid-filled photonic crystal fibers*

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A tunable thermo-optic intensity-modulated switch is investigated theoretically and numerically. It is based on the infiltration of temperature-sensitive mixture liquids into index-guiding photonic crystal fibers (PCFs). The switching function attributes to the thermo-optic effect of the effective refractive index of the cladding. The simulation illustrates that the switch presents a tunable transition point according to the concentration of the mixture liquids, and the on-off switching functionality can be realized within a narrow temperature range of 2 °C. The switches have wide application for innovative all-in-fiber optical communication and logic devices.

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Photonic crystal fibers (PCFs) are microstructured waveguides with an array of air holes located in the cladding and have been researched for many years[1,2]. The waveguide mechanism of PCFs may be explained as either modified total internal refraction (TIR)[3] or photonic bandgap (PBG)[4]. The properties of PCFs are determined by the size, shape and relative position of the air holes, which offer great freedom in the waveguide design and promise diverse applications in optical transmission, PCF lasers and PCF sensors[5,6]. Additionally, a unique ability of PCFs is that it accommodates advanced materials inside the air holes of the cladding[7], which leads to innovative functional devices, such as switches[8-10], attenuators[11], dispersion compensators[12] and filter[13]. Filling composite with high temperature-sensitive refractive index provides a platform for thermally controlled optical components. Wang and Jin[9] reported the optical switch based on temperature-controlled hybrid microstructure fiber, the extinction ratio of which is more than 30 dB via a narrow temperature adjustment of ±5 °C. Kerbage and Eggleton[11] presented a tapered microstructure optical fiber incorporated with polymer for a temperature-controlled variable attenuator in the operation temperature range of 80 °C. Miao[13] demonstrated the temperature tunability of PCF filled with Fe_3O_4 nanoparticle fluid for an intensity-modulated sensing element or a tunable gain equalization filter. However, the temperature transition point of the optic switches to date cannot be tunable, and the temperature adjustment is in the order of magnitude of 10 °C, which severely limits their practical application.

In this paper, we theoretically and numerically investigate a liquid-filled thermo-optic switch with a tunable transition point and more sensitive temperature on-off response. The mixture liquids of toluene and ethanol are filled into the cladding air holes in order to enhance the switching functionality. The temperature transition point of the switch is tunable simply by changing the concentration of the two components, and it presents an on-off light transmission within a narrow temperature adjustment of 2 °C. These characteristics provide a promising application for optical communication and logic devices.

According to the dependence of propagation characteristics on the parameters of PCFs, a greater air-filling ratio

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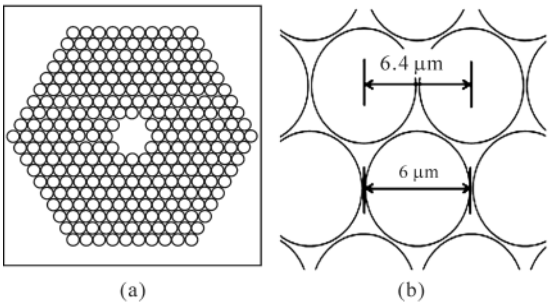
(D/Λ) is congenial to the confinement of mode fields and the temperature sensitivity[14]. Consequently, the cross-section of PCF in our simulation is plotted in Fig.1. The core is a defect of 2-ring air holes, and the cladding with 8 rings is a two-dimensional (2D) triangular arrangement. The inter-hole distance and the diameter of the air holes are Λ= 6.4 μm and D= 6 μm, respectively. The cladding diameter is 125 μm as conventional single-mode optical fibers for further fusion-splicing or coupling.



(a) (b)

Fig.1(a) Cross-section and (b) parameters of PCFs

The liquid-filled air holes with refractive index ranging from n_{toluene} to n_{ethanol} can be obtained by means of liquid mixing. The refractive indices of the two liquids are described by Sellmeier equations at 20 °C[15]. Generally, the refractive index of n_{mixture} as a function of concentration of ethanol ρ can be expressed as

$$n_{\text{mixture}} = [n_{\text{ethanol}}|_{T=20°\text{C}} + \mathrm{d}n_{\text{ethanol}}/\mathrm{d}T\times(T-20)]\times f(\rho) + [n_{\text{toluene}}|_{T=20°\text{C}} + \mathrm{d}n_{\text{toluene}}/\mathrm{d}T\times(T-20)]\times g(1-\rho)\ , \tag{1}$$

where the thermal coefficients of the refractive indices are $\mathrm{d}n_{\text{ethanol}}/\mathrm{d}T$=-3.940 × 10^{-4} K^{-1} and $\mathrm{d}n_{\text{toluene}}/\mathrm{d}T$=-5.273 × 10^{-4} K^{-1}, respectively, which are independent of wavelength or temperature.

Under the assumption that the index of the mixture is linear with the concentration[16], the expressions are simplified as $f(\rho)=\rho$ and $g(\rho)=1-\rho$. The thermal coefficient of mixture liquid, which is in the order of 10^{-4} K^{-1}, is two orders of magnitude higher than that of SiO_2 (8.6 × 10^{-6} K^{-1}). As a result, the thermo-optic coefficient and the refractive index of the background material are considered independent of temperature (n_{silica}=1.444 at 1550 nm)[17].

The relationships between the material refractive index and temperature are illustrated in Fig.2. Taking the volume ratio of toluene and ethanol as 7:3 for example, when the temperature decreases from 20 °C to about 13 °C which is the crossing point of mixture liquid and SiO_2, the indices of the core and cladding get equivalent, and the light can not be effectively confined in the core, leading to the operation as thermo-optic switch. The transition point of the switch presents a tunable range simply as a function of component concentration, which is about 38 °C with the mixture volume ratio of 8:2.

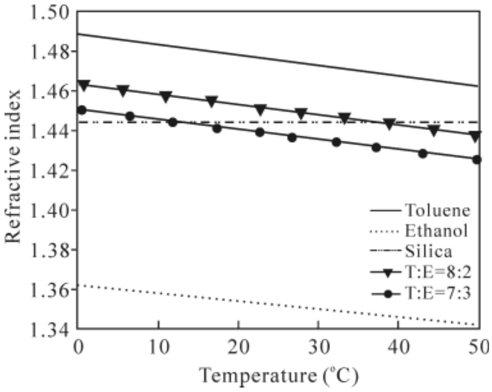


Fig.2 Material refractive index as a function of temperature with different volume ratios of toluene and ethanol

The optical switching properties are numerically investigated on the basis of the full-vector finite element method (FEM) combined with the anisotropic perfectly matched layer (PML). The confinement loss (dB/m), arising from the imaginary part of the effective complex refractive index n_{eff}, is given as

$$CL(\mathrm{dB/m}) = 20\log_{10}\mathrm{e}\times\mathrm{Im}(\beta_{\text{eff}}) = 8.686\times\mathrm{Im}(n_{\text{eff}})\times k_0. \tag{2}$$

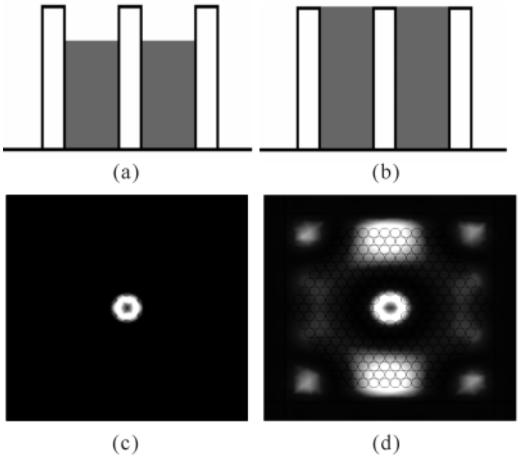
The transmittance of incident light is defined as:

$$T = \frac{P_{\text{out}}}{P_{\text{in}}} = 10^{-\frac{CL(\mathrm{dB/m})\times L}{10}}\ , \tag{3}$$

where L denotes the length of PCF.

With the volume ratio of toluene and ethanol as 7:3, the waveguide refractive index profiles and the corresponding distributions of fundamental modes at 16 °C for (a) and (c) as well as 14 °C for (b) and (d) are plotted in Fig.3. When the temperature drops from 16 °C to 14 °C, the refractive index of liquid-filled cladding increases and approximates to that of SiO_2 background, and the PCF gradually transforms into a non-ideal waveguide.

The practical switching functions are illustrated in Fig.4,



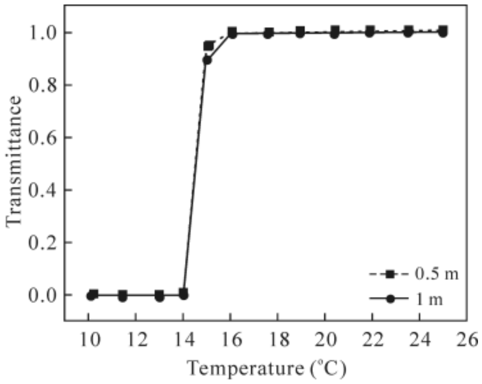
(a) (b)

(c) (d)

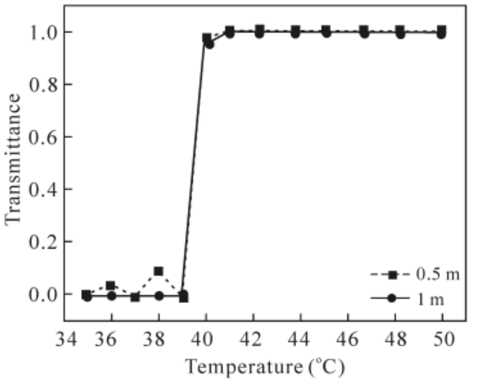
Fig.3 Refractive index profiles and fundamental mode fields at 16 °C for (a) and (c) as well as 14 °C for (b) and (d)

in which the transmittance through the fiber is a function of temperature with the incident wavelength of 1550 nm. Fig.4 (a) indicates when the temperature decreases from 16 °C to 14 °C, the fundamental mode in the core leaks into cladding, which results in the increase of confinement loss and the absorption by the liquids, and the transmittance attenuates from 100% to nearly 0. Comparing Fig.4(a) with(b), it is obvious that the transition point is tunable according to the component concentration. The relationship between the critical temperature and concentration of ethanol is plotted in Fig.5. Therefore, the mixture liquid infiltrated PCF can be developed as a promising tunable in-fiber optic switch within a narrow temperature adjustment of 2 °C.

In conclusion, with appropriate mixture of temperature-sensitive liquids, the liquid-filled PCFs can be developed as an innovative thermo-optic intensity-modulated switch. Different transition points can be realized according to the concentration of mixture liquids. And it presents an on-off operation within a narrow temperature adjustment of 2 °C. The switch indicates that compact, high-performance optical devices will be developed for all-in-fiber optical communication and logic devices.



(a) 7:3



(b) 8:2

Fig.4 Transmittance as a function of temperature at the length of PCF *L*=0.5 m and 1 m with different volume ratios of toluene and ethanol

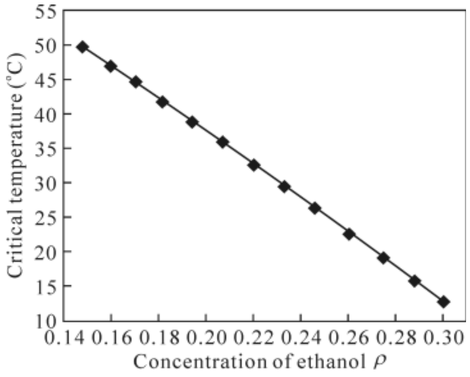


Fig.5 Relationship between the critical temperature and concentration of ethanol *ñ*

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