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Negative dispersive temperature sensor based on H-shaped photonic crystal fiber filled with air and ethanol

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Two H-shaped photonic crystal fiber (H-shaped PCF) having circular holes whose inner ring is filled with air and ethanol respectively is proposed for sensing of temperature. It is suitable for detecting birefringence, negative dispersion, temperature and temperature sensitivity by finite element method. Simulation results are analyzed by Rsoft FEMSIM software which shows that sensor has good linearity. The sensitivity of H-shaped fiber after filling air is -0.77463 nm/°C and ethanol is -0.69434 nm/°C at wavelength of 1.55 μm. High value of birefringence 6.057×10^{-2} is obtained by the filling of ethanol at 1.55 μm. The proposed sensor can be used in many applications in food industry and medical testing.

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Keywords: Photonic crystal fiber, Temperature sensor, Finite element method, Sensitivity, Temperature, Dispersion

1. Introduction

Photonic crystal fiber (PCF) has many prominent applications in the development of unique optical devices due to its unique structure and special optical characteristics, including adjustable and negative dispersion, large mode field area, high birefringence, low confinement loss etc. In current years, the optical sensing based on the PCFs has become an important part of research [1, 2]. Among these, the temperature sensor PCF has attracted great research interests since it plays important roles in the fields of different medical testing, aerospace exploration and the food industry [29].

The temperature sensing based PCF can be designed by filling various liquid to the inner rings of capillary tubes. With the development of PCF fabrication and multi-step infiltration technologies are developed, different sensing liquids like toluene, ethanol and liquid crystal have been filled into the designed PCF. In 2016, Dong et al. reported an ethanol-filled band-gap PCF for the temperature sensing [3-5]. In 2017, Ma et al. proposed a toluene-filled PCF for the temperature sensing whose average sensitivity was achieved as −6.02 nm/°C [6].

In 2019, Mirza et al. analyzed a water-filled dual-core PCF (DC-PCF) for the temperature sensor, where the maximum value of sensitivity was reached at 818 pm/°C in the detection range from 30 °C to 70 °C [7].

In 2017,Weng et al. in investigated a D-shaped liquid-filled PCF based on the SPR (Surface Plasmon Resonance) for the temperature sensing, where the average value of temperature sensitivity was found to be −3.635 nm/°C in the temperature range from 20°C to 50 °C [8].

Recently, different types of glasses are usually used as alternative materials in the design of the all-solid core PCFs [9]. However, because of the difference between the refractive index of silica and glasses, their different physical characteristics such as the transition temperature, viscosity coefficient, thermal expansion coefficient, have obvious difference. Therefore, it is a great challenge to fabricate the glasses-based all-solid core PCFs in practice. However, a PC (Photonic Crystal) structure can be more complex in that it has a two-dimensional periodic dielectric arrangement, referred to as a two-dimensional PC (2DPC), by a volumetric periodicity, which is forming a three-dimensional PC (3DPC) [10–12]. Photonic crystal fibres (PCFs) have advantages such as minimal size, tunable geometrical parameters and birefringence phenomena, which make them a suitable choice for temperature sensors [29, 30]. Furthermore, by changing the geometrical parameters of the PCF structure, the effective RI of the core-guided mode can be changed.

In 2022, Chhipa et al. designed 2D photonic crystal ring resonator, where data rate is 4.48 Tbps, response time of 222.76 fs and compact size of 140.84 μm^2 [13]. In 2019, Gharsallah et al. designed a bio-sensors with sensitivity reached at 650 nm/RIU and detection limit of 10^{-3} [14]. In 2021, Chhipa et al. designed a ring resonator with contrast ratio of (CR) 22.06 dB and response time of 0.14 ps [15].

In this paper, we proposed two solid cores H-shaped PCF for temperature sensing; one of them has inner ring filled with air and second one has inner ring filled with ethanol. In this structure air holes are arranged in square lattice which finally form an H-shaped PCF. The proposed structure is formed by the capillary tube, and the background material is silica (refractive index 1.45) [31].

The performance of temperature sensor of the proposed H-shaped PCF is numerically investigated by the finite element method (FEM). The simulation results show that the different value of sensitivity and temperature at different wavelength with both filling air and ethanol. At the wavelength of 1.55 μm its value after filling air and ethanol is -0.77463 nm/°C and -0.69434 nm/°C respectively at a particular temperature range. It is also obtained that the proposed temperature sensor based on the H-shaped PCF has high value of birefringence.

2. Design of H-shaped PCF and theoretical modeling

The cross-sectional view of the designed H-shaped PCF temperature sensor is shown in Fig. 1 and 3-D view is in Fig. 2. The sensor characteristics are examined by the FEM with the help of RSOFT software. The structure consists of different circular air holes in H-shaped lattice. The inner ring air hole is filled with the ethanol having the refractive index (n_e) of 1.36. The triangular lattice constant is Λ whose value is 1.2 μm, the diameter of air holes is 1 μm and the background material is the silica, whose refractive index is n_{silica}. Compared with the conventional solid core PCF, the designed H-shaped PCF filled with ethanol can achieve the better performances in the temperature sensing.

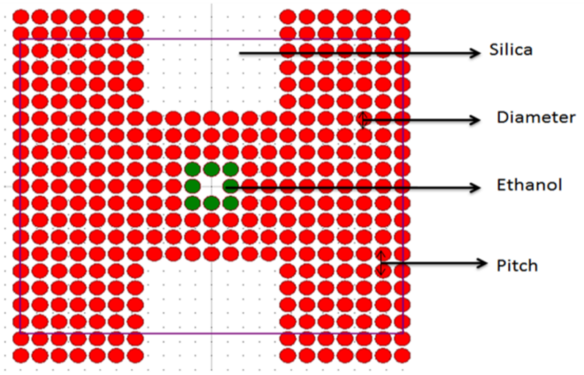


Fig. 1. Schematic illustration of the designed H-shaped PCF (colour online)

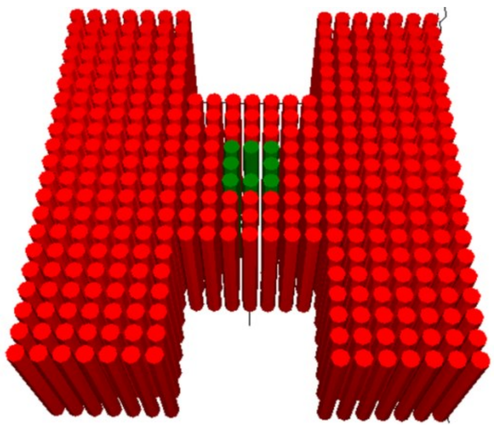


Fig. 2. 3-D view of H-shaped PCF (colour online)

The reasons are considered as follows. First, the structural parameters of the H-shaped PCF could be adjusted more flexible. Second, the thermal optical coefficient (3.94×10^{-4}/°C) of the ethanol is in the orders of higher magnitude than that of the silica (8.6×10^{-6}/°C), which can improve the temperature sensitivity. Thirdly, the solid jacket is pressure resistant, and the liquids can be conveniently filled.

The FEM is used to find the propagation and temperature sensing characteristics of the designed H-shaped PCF. The FEM divides a PCF the cross-section within transverse x, y plane a patchwork of triangular components of varying sizes, shapes, and refractive indices. It may also be used to investigate fibers with non-periodic air-hole configurations.

The refractive index of n_{silica} (silica) can be calculated from [16]

$$n^2_{\text{silica}}(\lambda, T) = (1.31522 + 6.90754 \times 10^{-6}T) + \\ + \frac{(0.788404 + 23.5835 \times 10^{-6}\,T)\lambda^2}{\lambda^2(0.0110199 + 0.584758 \times 10^{-6}T)} + \\ + \frac{(0.91316 + 0.548368 \times 10^{-6}T)\lambda^2}{\lambda^2 - 100} \qquad (1)$$

where λ is the free space wavelength in the range of UV to 1.7 μm and T is the temperature in degree celsius (°C) in the range of -165.4 to 83.3° C.

The refractive index of ethanol $n_e$can be obtained as [17, 18]

$$n_e = 1.36048 - \alpha(T - T_0) \qquad (2)$$

where α is the thermo optic coefficient whose value is chosen as $\alpha = 3.94 \times 10^{-4}$/°C, T is ambient temperature and T_0 is room temperature of 20 °C. Its value is higher than silica which is (8.6×10^{-6}/°C) [19].

The n_{eff} value varies depending on the mode and frequency of the wave and can be approximated using software designed for mode solving. The waveguide's refractive index profile determines the n_{eff} values.

The effective refractive index (n_{eff}) can be analyzed as [20]

$$n_{\text{eff}} = \frac{\beta}{K_0} \qquad (3)$$

where K_0 is wave number and β is propagation constant.

The birefringence (B) is the difference between real part of effective refractive index along X pole and Y pole which depends on operating wavelength.

It is calculated by the following equation [21]:

$$B = \text{Re}|\text{neff}_x - \text{neff}_y| \qquad (4)$$

where neff_x, neff_y are effective indices of X and Y polarized mode.

The dispersion of the designed structure can be evaluated by [22]

$$D = -\frac{\lambda}{c}\frac{d^2\text{Re}[n_{\text{eff}}]}{d\lambda^2} \qquad (5)$$

Here, λ, c, and Re[neff] are wavelength, velocity of light wave and real part of effective refractive index respectively.

The temperature sensitivity is evaluated as [23-26]:

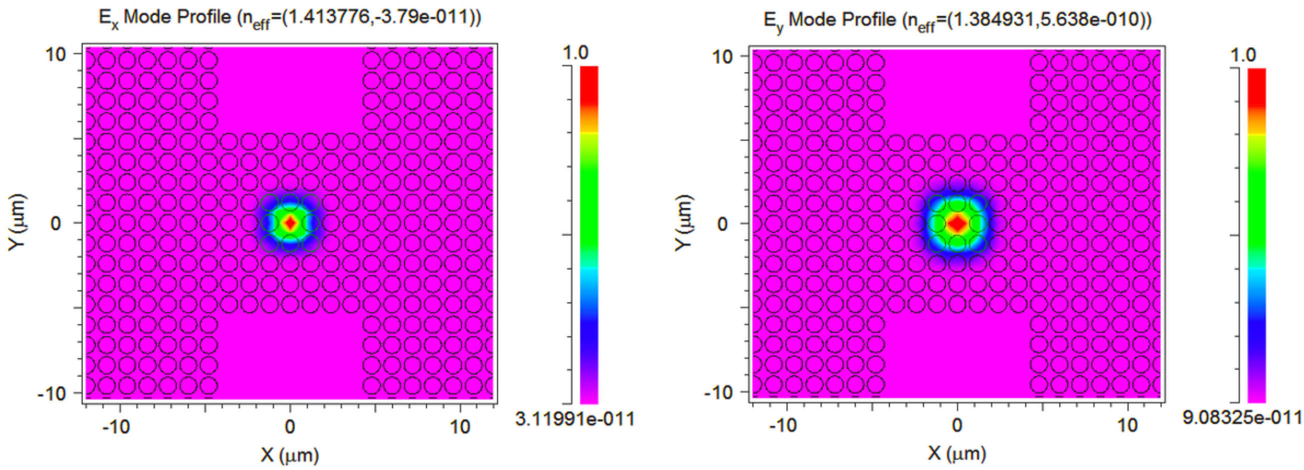
$$S = \frac{\Delta\lambda_{Peak}}{\Delta T}\ (\text{nm}/^{o}\text{C}) \qquad (6)$$

where λ_{Peak} is the variable quantities of resonance peaks or peak wavelength and ΔT is the change in temperature.

3. Simulation results and discussion

The electric field distribution of designed H- shaped PCF in x-polarized direction and y-polarized direction are shown in Fig. 3(a) and (b) respectively.

The power is mostly concentrated in the center part of the proposed H-shaped PCF in which inner ring is filled with air and ethanol.



3(a) x- polarized mode 3(b) y- polarized mode

Fig. 3. Electric field distribution of polarized mode (colour online)

The impact of the designed structure after filling air and ethanol to the birefringence is shown in Fig. 4. Birefringence is calculated by using (4):

It is found that birefringence progressively increases as the wavelength increases from 1.0 µm to 1.7 µm because the difference of effective refractive index increases by increasing the wavelength. It is the difference of real part of n_{eff} about x and y polarization and n_{eff} decreases linearly by increasing wavelength. So the birefringence increases.

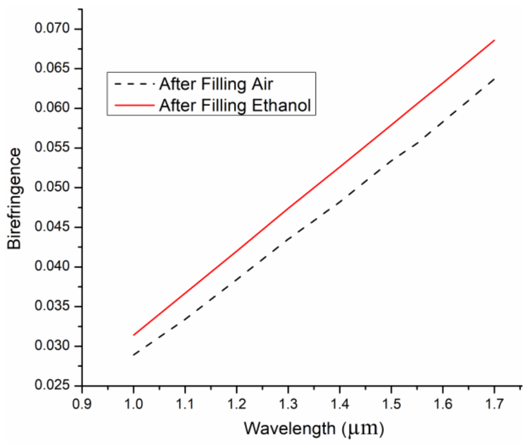
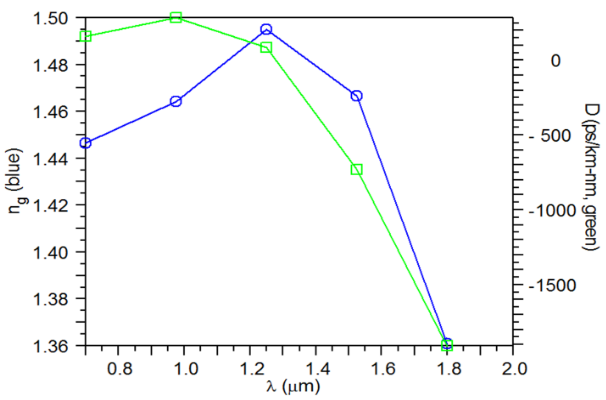
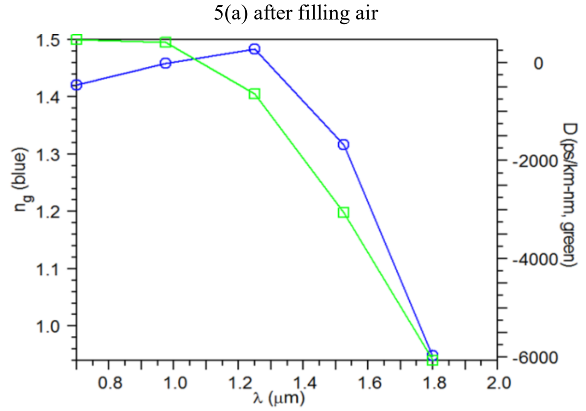


Fig. 4. Birefringence vs. wavelength graph after filling air and ethanol (colour online)

Higher value of birefringence are obtained after filling of ethanol whose value is 6.057 × 10^{-2}, 6.86 × 10^{-2} and lower value are obtained after the filling of air as 5.56 × 10^{-2}, 6.37 × 10^{-2} at the operating wavelength of 1.55 µm and 1.7 µm respectively.



5(a) after filling air



5(b) after filling ethanol

Fig. 5. The dispersion graph with respect to filling of air and ethanol (colour online)

Fig. 5 (a) and (b) of designed H-shaped temperature sensor PCF shows the dispersion curve with respect to the wavelength from 0.7-1.8 µm. In this figure green colour represent the dispersion (D) curve and blue colour shows group index (n_g). The relation for n_g is given by $n_g = n_{eff} - \lambda. (dn_{eff}/d\lambda)$ [27-29]. It is observed from Fig. 5(a) that the dispersion graph of air filled PCF at first increases from 0.7-1.0 µm and then decreases gradually after increasing the wavelength from 1.0-1.8 µm. Similarly Fig. 5(b) show that after filling of ethanol of designed H-shaped PCF at first the value of dispersion becomes constant at the wavelength of 0.7-1.0 µm and then decreases after increasing the wavelength from 1.0- 1.8 µm. In Fig. 5(a) and (b), the proposed temperature sensor shows the negative dispersion coefficient value approximately -2000 ps/km-nm and -6000 ps/km-nm respectively. It is easily noticed that ethanol filled structure shows the more negative value of dispersion coefficient.

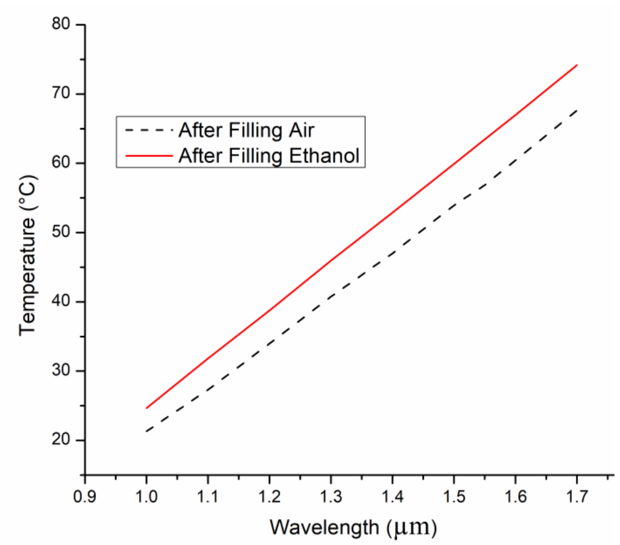
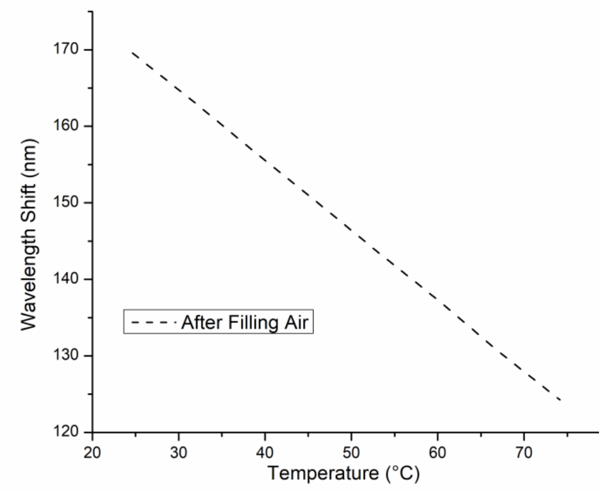
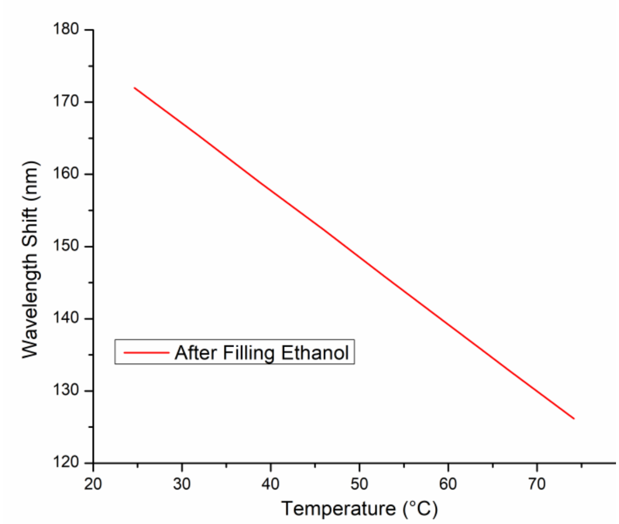


Fig. 6. Temperature curve with respect to wavelength graph in °C (colour online)

The relation of temperature (T) and birefringence (B) can be as $B = 7{,}51 \times 10^{-6}T + 12{,}9 \times 10^{-4}$ [28]. In Fig. 6, it is observed that after increasing the wavelength from 1.0-1.7 µm the value of temperature increases in both case of air filled and ethanol filled H-shaped PCF. It shows from Fig. 6 that higher temperature have wider wavelength because higher wavelength correspond to high energy level. At the wavelength of 1.55 µm, 1.7 µm the value of temperature in air filled design is 56.85 °C, 67.64 °C and ethanol filled structure is 63.47 °C, 74.16 °C respectively.



7(a) after filling air



7(b) after filling ethanol

Fig. 7. The wavelength shift graph with respect to temperature in nm (colour online)

A wavelength shift (in nm) has been observed from Figs. 7(a) and 7(b) when temperature changes from 21 °C to 67 °C for air and 24 °C to 74 °C for ethanol. The wavelength shift as a function of temperature is reported and linearity can be obtained.

The sensitivity is a key performance indicator which is calculated as the ratio of resonance wavelength shift and change in temperature. It is evaluated by using (6):

Temperature sensitivity is basically depends on the shift of resonance wavelength, if the resonance peak are shifted by larger amount then higher value of sensitivity is achieved. From Fig. 8 it is observed that the value of sensitivity increases with the increasing of wavelength from 1.0-1.7 µm. For air filled, the sensitivity response ranges from -1.11436 to -0.60039 nm/°C and for ethanol filled its value is from -1.03337 to -0.50457 nm/°C in wavelength of 1.0-1.7 µm respectively.

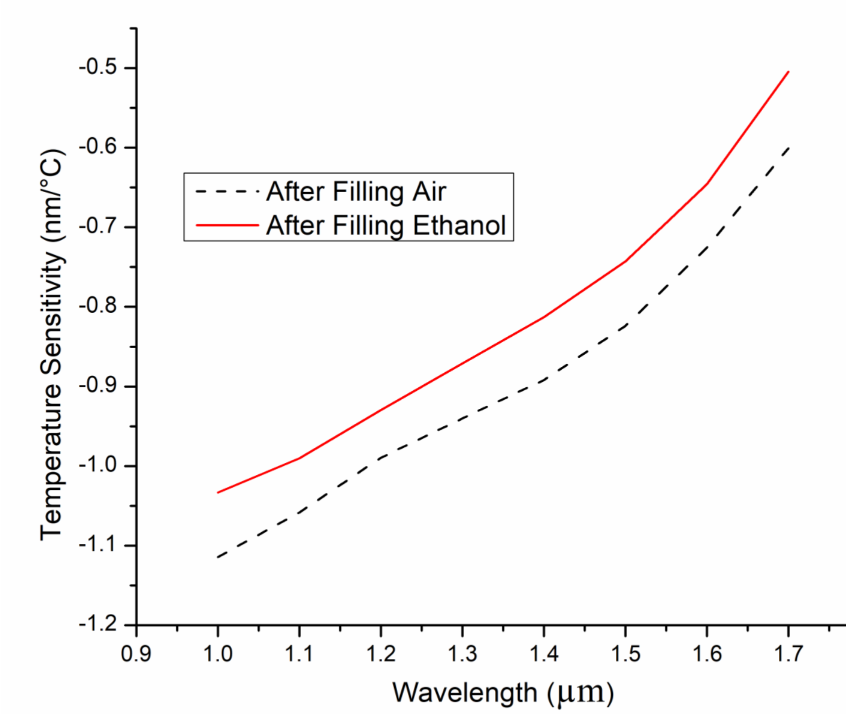


Fig. 8. Temperature Sensitivity graph with respect to wavelength in nm/°C (colour online)

Table 1. Comparison between the designed H-shaped PCF temperature sensor with other report

Ref.	Structure	T (°C)	S (nm/°C)	B	Dispersion (ps/nm-km)
[5]	Ethanol-filled photonic band gap fiber	25-50	-0.292	-	-
[6]	Soilid-core PCF	-80-90	-6.02	-	-
[7]	Dual-core PCF filled with water	30-70	0.818	-	-
[8]	D-shaped PCF based on SPR	20-50	-3.635	-	-
Own work	H-shaped PCF filled with air and ethanol	21-67 24-74	-0.60039 -0.50457	6.37×10^{-2} 6.86×10^{-2}	-2000 -6000

4. Conclusion

In summary, an H-shaped PCF filled with air and ethanol is proposed for sensing the temperature and the designed structure are analyzed by Rsoft FEMSIM software. The inner rings of the designed PCF are filled with air and ethanol. By optimizing the PCF structure parameters, the temperature sensitivity of structure after air filled and ethanol filled is -0.77463 and -0.69434 nm/°C at the operating wavelength 1.55 µm respectively. Also the sensing temperature of air is 56.85 °C and ethanol is 63.47 °C at wavelength of 1.55 µm. The maximum value of temperature sensitivity of air filled and ethanol filled can achieve -0.60039 nm/°C and -0.50457 nm/°C respectively. The study gives a new idea for research and application of H-shaped PCF temperature sensor.

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