High-sensitivity temperature sensor based on an alcohol-filled photonic crystal fiber loop mirror

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A compact temperature sensor based on a fiber loop mirror (FLM) combined with an alcohol-filled high-birefringence photonic crystal fiber (PCF) is proposed and experimentally demonstrated. The output of the FLM is an interference spectrum with many resonant dips, of which the wavelengths are quite sensitive to the change of the refractive index of the filled alcohol for the interference of the FLM. Simulation analysis predicts a high temperature sensitivity, and experimental results show it reaches up to 6.6 nm/°C for the 6.1-cm-long PCF used in the FLM.

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Fiber loop mirrors (FLMs) have been important devices in the optical sensing and communications areas [1]. Usually, an FLM consists of a highly birefringent (HiBi) fiber combined with a 3 dB coupler. The former can introduce optical path difference of the two counterpropagating waves and cause an interferential spectrum, which is used as a sensing element. Various kinds of sensors based on FLMs have been demonstrated for applications, such as temperature sensors, strain sensors, and biochemical sensors [2–4]. Utilizing the high temperature sensitivity of birefringence of conventional HiBi fibers, temperature sensors based on FLMs have been reported and have a sensitivity (~0.94 nm/°C) that is ~94 times higher than that of fiber Bragg grating (FBG) sensors [3]. However, due to the limited birefringence of conventional fibers, the HiBi fiber used in the FLM sensor is usually quite long (~72 cm), which is not convenient in practical use.

Photonic crystal fibers (PCFs) incorporate a number of air holes that run along the length of the fiber [5,6]. By arranging the geometry or distribution of the core and the air-hole cladding, PCFs can have ultrahigh birefringence, and therefore HiBi-PCFs have been the best choice to make FLMs [7–10]. In strain sensors based on HiBi-PCF FLMs, the length of HiBi-PCF is shortened to ~8 cm, and thus the stability of the total system increases greatly [8,10]. However, HiBi-PCF FLMs cannot be used to measure temperature, because HiBi-PCFs have a low thermo-optic and thermoexpansion coefficient.

In this Letter, we demonstrate a compact temperature sensor by inserting a short alcohol-filled HiBi-PCF into an FLM. Because of the high temperature sensitivity of the filled alcohol, an extremely high temperature sensitivity can be realized by measuring the wavelength shift of the resonant dips of the alcohol-filled HiBi-PCF FLM.

The proposed temperature sensor, as shown in Fig. 1, consists of a 3 dB coupler and a short alcohol-filled PCF. The main FLM principle is summarized as following. Input light is split by the 3 dB coupler equally into two counterpropagating waves that subsequently recombine at the coupler after propagating around the loop. These two waves produce an optical path difference after transmitting through the HiBi-PCF because of its birefringence. Therefore an interference response with many dips generates and displays at output, which is approximately a periodic function of the wavelength, given as [3]

$$f = (1 - \cos\theta)/2, \tag{1}$$

where $\theta = 2\pi BL/\lambda$ is the phase difference of the FLM. λ is the wavelength, $B = n_x - n_y$ is the birefringence of the HiBi-PCF, n_x and n_y are the effective refractive index at the slow and fast axes, and L is the length of the HiBi-PCF. The transmission dip wavelengths are the resonant wavelengths satisfying $2\pi BL/\lambda_{\mathrm{dip}} = 2k\pi$, where k is any integer. Thus, the resonant dip wavelengths can be described as

$$\lambda_{\mathrm{dip}} = BL/k. \tag{2}$$

The wavelength spacing between transmission dips can be expressed as $S = \lambda^2/BL$.

We choose alcohol to fill the HiBi-PCF, since it is a conventional and easily poured liquid with a high temperature sensitivity. Here, an alcohol-filled HiBi-PCF is inserted into an FLM as a temperature sensing head.

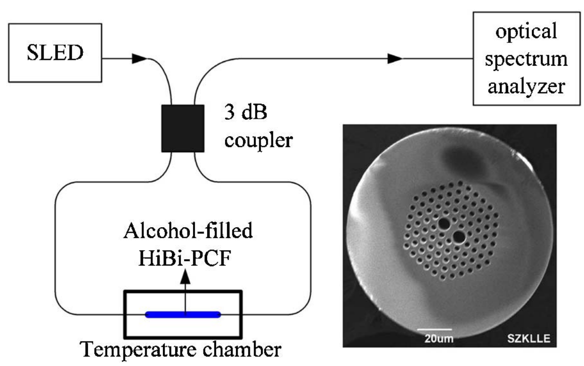

Fig. 1. (Color online) Experimental setup for a temperature sensor based on an FLM. Inset: SEM of the used HiBi-PCF.

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Birefringence change ΔB and length change ΔL of the alcohol-filled HiBi-PCF caused by temperature leads to a wavelength shifting of the resonant dips according to Eq. (2). The relationship between the dip wavelength change $\Delta\lambda_{\mathrm{dip}}$, ΔB, and ΔL is simply expressed as

$$\Delta\lambda_{\mathrm{dip}} = (\Delta BL + B\Delta L)/k, \tag{3}$$

where ΔB is the birefringence change caused by the thermo-optic effect, including that of the original HiBi-PCF and that of the filled alcohol, and ΔL is the length change caused by the thermoexpansion effect, which also includes the elongation of the original HiBi-PCF and the expansion of the filled alcohol.

We neglect ΔB and ΔL caused by the HiBi-PCF itself because of the good thermal independence of the HiBi-PCF [7–10]. Further, ΔL caused by the thermoexpansion of the filled alcohol is also ignored, since the volume of alcohol filling the air holes of the HiBi-PCF is small. Thus, $\Delta\lambda_{\mathrm{dip}}$ mainly depends on ΔB of the alcohol-filled HiBi-PCF. The birefringence–temperature dependence of the alcohol-filled HiBi-PCF is analyzed using a full-vector finite element method . The diameters of the bigger and smaller holes are 7 and 3.2 μm, respectively, and the pitch length between centers of two adjacent holes is 5.46 μm, according to the HiBi-PCF used in experiment. The refractive index of pure silica and the filled alcohol is taken as 1.4457, the empirical value, which is calculated by an empirical equation according to [11].

Figure 2 shows the empirical temperature dependence of the refractive index of alcohol and the theoretical temperature dependence of the birefringence of the alcohol-filled HiBi-PCF. With the temperature rising, the refractive index of alcohol decreases linearly, while the birefringence of the alcohol-filled HiBi-PCF increases linearly. The mode fields of the two orthogonal polarizations at 20 °C are shown in the insets of Fig. 2. The birefringence of the alcohol-filled HiBi-PCF is calculated at 3.5×10^{-4} at 20 °C. P_t is defined as a thermo-optic constant on the birefringence of the alcohol-filled HiBi-PCF, which is equal to the slope of the temperature dependence curve of birefringence and is calculated at 1.5×10^{-6}/°C. According to Eqs. (2) and (3), the relationship between the resonant dip wavelength shift $\Delta\lambda_{\mathrm{dip}}$ and the temperature change ΔT can be deduced as

$$\Delta\lambda_{\mathrm{dip}} = \Delta BL/k = \frac{LP_t}{k}\Delta T = \frac{\lambda_{\mathrm{dip}}}{B}P_t\Delta T. \tag{4}$$

Based on the above equation, the temperature sensitivity of the alcohol-filled HiBi-PCF FLM is related to λ_{dip}, P_t, and B. A high temperature sensitivity depends on a long wavelength λ_{dip} of the measured resonant dip, a high thermo-optic constant P_t, and a small birefringence B of the filled HiBi-PCF.

The HiBi-PCF used in our experiment is provided by Yangtze Optical Fibre and Cable Company, and the cross-sectional scanning electron micrograph (SEM) is shown in the insertion of Fig. 1. The HiBi-PCF has a birefringence of 10.2×10^{-4} at 1550 nm, and the length is 6.1 cm. After the HiBi-PCF is filled with alcohol by air-hole capillary force, the birefringence of the PCF reduces significantly, which brings the advantages of a larger wavelength space between two resonant dips and a wider measurement range. Both ends of the alcohol-filled HiBi-PCF are spliced to conventional single-mode fiber (SMF) using a regular arc splicing machine (Fujikura FSM 60). The PCF-SMF splicing loss is ~3 dB, which is relatively large and caused by mismatching of mode field and numerical apertures between the HiBi-PCF and SMF. The total insertion loss of the FLM is ~8.5 dB. However, it would not affect experimental results, since we directly measure the resonant dip wavelength shift. A broadband superluminescent light-emitting diode (SLED) source with 200 nm wavelength range is used as an input light source. The transmission spectra of the FLM are measured by an optical spectrum analyzer with a wavelength resolution of 0.1 nm.

Figure 3 shows the transmission spectrum of the alcohol-filled HiBi-PCF FLM at room temperature (20 °C). Two resonant dips of the FLM display in the wavelength range from 1400 to 1600 nm. One is at the wavelength of 1455.8 nm (dip A) with a 15.5 dB extinction ratio; the other is at about 1549.8 nm (dip B) with a 10.5 dB extinction ratio. The wavelength spacing between these two dips is ~94 nm, and the corresponding birefringence of the alcohol-filled HiBi-PCF is ~3.9×10^{-4} at 20 °C, which is close to the theoretical value (~3.5×10^{-4}). The little difference between the experimental and theoretical

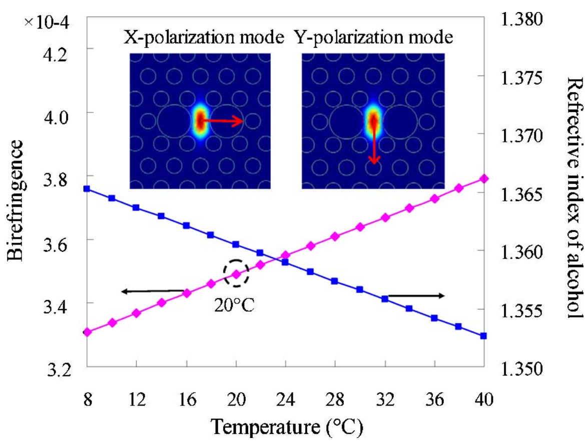

Fig. 2. (Color online) Temperature dependence of the refractive index of alcohol and the birefringence of the alcohol-filled HiBi-PCF in theory. Insets: x and y polarization mode fields of the alcohol-filled HiBi-PCF at 20 °C.

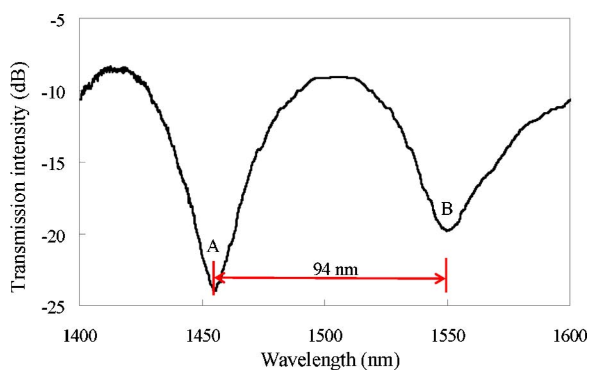

Fig. 3. (Color online) Transmission spectrum of the alcohol-filled HiBi-PCF FLM at 20 °C.

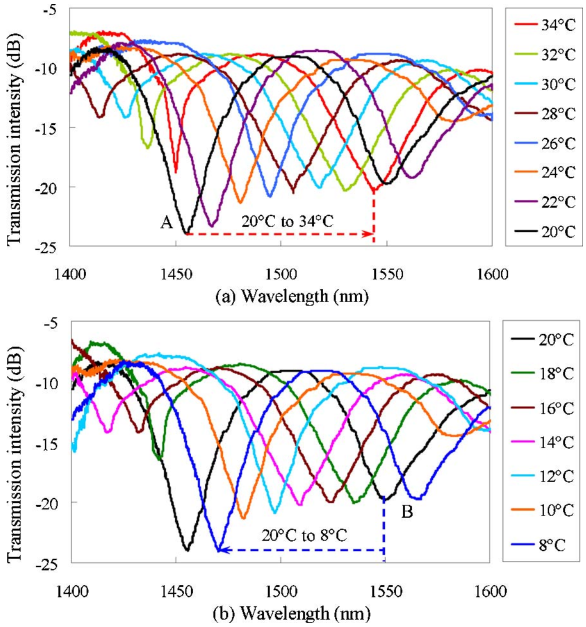

Fig. 4. (Color online) Transmission spectra of the alcohol-filled HiBi-PCF FLM (a) when the temperature increases from 20 °C to 34 °C and (b) when the temperature decreases from 20 °C to 8 °C.

values may be caused by an error in air-hole dimensions of the HiBi-PCF according the SEM.

In our experiment, the temperature characteristic of the alcohol-filled HiBi-PCF FLM is tested by placing the alcohol-filled HiBi-PCF of the FLM in a temperature-controlled container. Figures 4(a) and 4(b) show the transmission spectra of the alcohol-filled HiBi-PCF FLM at a temperature range of 20 °C to 34 °C and 8 °C to 20 °C, respectively. Dip A redshifts from 1455.8 to 1543.7 nm, with the temperature increasing gradually from 20 °C to 34 °C at the same time the extinction ratio of dip A decreases. Dip B blueshifts from 1549.8 to 1470.4 nm, with the temperature decreasing gradually from 20 °C to 8 °C.

Figure 5 shows the experimental relationship between temperature and the resonant wavelength of dip A and dip B. The fitting curves can be expressed as $y = 6.2176x + 1331.7$ for dip A and $y = 6.6335x + 1416.7$ for dip B, and the high fitting degrees 0.9997 and 0.9995 mean the linearity of the resonant wavelength to temperature is excellent. The experimental temperature sensitivities of dip A and dip B are ~6.2 nm/°C and ~6.6 nm/°C, respectively. The theoretical sensitivities are ~6.1 nm/°C and ~6.5 nm/°C, respectively, from Eq. (4). It is clear that the theoretical and the experimental results are in accordance. The temperature sensitivity of the alcohol-filled HiBi-PCF FLM is very high, about 660 and 7 times higher than that of an FBG (~0.01 nm/°C) and that of an FLM made of a conventional HiBi fiber with a 72 cm length (~0.94 nm/°C), respectively.

In practical uses, for a wider measurement range of temperature, the length L of the HiBi-PCF can be shortened in order to widen the spacing between two resonant dips based on $S = \lambda^2/BL$. For example, when the alcohol-filled HiBi-PCF is 1 cm, the spacing of the proposed FLM sensor is ~564 nm. It can provide the measurement range of ~84 °C with the same temperature sensitivity (~6.6 nm/°C) according to Eq. (4), in which the length of the sensing fiber is the same as the length of FBG sensing head and is shortened 72 times more than that of the conventional HiBi-FLM temperature sensor.

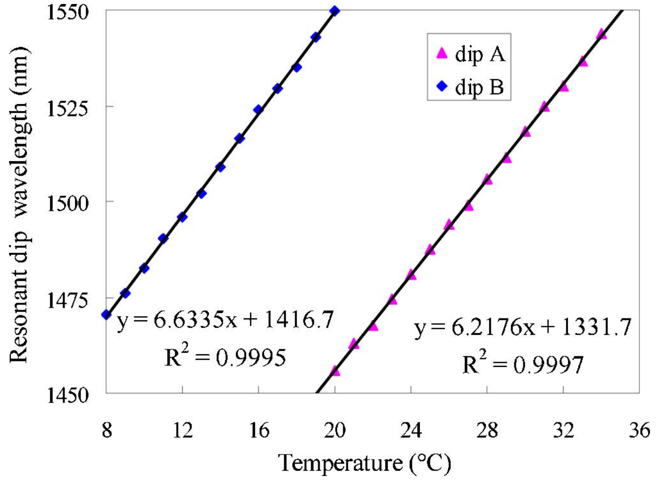

Fig. 5. (Color online) Relationship between temperature and the resonant wavelength of dip A and dip B.

In conclusion, we have proposed and demonstrated a novel compact temperature sensor based on an alcohol-filled HiBi-PCF FLM. Because of the high thermo-optic effect of the alcohol-filled HiBi-PCF, the highly sensitive fiber temperature sensor has been realized. Experimental results of the proposed HiBi-PCF FLM temperature sensor show that the sensitivity is as high as 6.6 nm/°C, which is 660 and 7 times higher than that of an FBG and that of the FLM made of a conventional HiBi fiber.

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References

1. D. B. Mortimore, J. Lightwave Technol. **6**, 1217 (1988).
2. E. De La Rose, L. A. Zenteno, A. N. Starodumov, and D. Monzon, Opt. Lett. **22**, 481 (1997).
3. Y. Liu, B. Liu, X. Feng, W. Zhang, G. Zhou, S. Yuan, G. Kai, and X. Dong, Appl. Opt. **44**, 2382 (2005).
4. O. Frazão, B. V. Marquesa, P. Jorge, J. M. Baptista, and J. L. Santos, Sens. Actuators B **135**, 108 (2008).
5. T. A. Birks, J. C. Knight, and P. St. J. Russell, Opt. Lett. **22**, 961 (1997).
6. A. Ortigosa-Blanch, J. C. Knight, W. J. Wadsworth, J. Arriaga, B. J. Mangan, T. A. Birks, and P. St. J. Russell, Opt. Lett. **25**, 1325 (2000).
7. C.-L. Zhao, X. Yang, C. Lu, W. Jin, and M. S. Demonkan, IEEE Photon. Technol. Lett. **16**, 2535 (2004).
8. X. Dong and H. Tam, Appl. Phys. Lett. **90**, 151113 (2007).
9. H. Y. Fu, H. Y. Tam, L.-Y. Shao, X. Dong, P. K. A. Wai, C. Lu, and S. K. Khijwania, Appl. Opt. **47**, 2835 (2008).
10. W. Qian, C.-L. Zhao, X. Dong, and W. Jin, Opt. Commun. **283**, 5250 (2010).
11. Y. Yu, X. Li, X. Hong, Y. Deng, K. Song, Y. Geng, H. Wei, and W. Tong, Opt. Express **18**, 15383 (2010).