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Temperature and strain discrimination using two parallel connected Sagnac loops based on character-1 shaped polarization-maintaining fiber

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ABSTRACT

A fiber sensor configuration suitable for discrimination of temperature and strain is presented. The sensor head is composed of two parallel concatenated Sagnac loops based on character-1 shaped polarization-maintaining fiber (PMF). The two Sagnac loops include different sections of character-1 shaped PMFs, and show different sensitivity to temperature and strain. By monitoring the wavelength shift of the two dips in the transmission spectrum, simultaneous measurement of temperature and strain is obtained. The sensitivity for strain and temperature are measured to be 14.46 pm and −0.54 nm.

1. Introduction

The high-birefringence (Hi-Bi) fiber based Sagnac loop has attracted wide attention for its applications in optical communication and sensing, and it can be used to measure temperature, strain, curvature, displacement and liquid level [1–4]. The Hi-Bi fiber Sagnac loop brings several merits, including easy manufacture, good stability, great flexibility and low cost [5].

In optical sensing, optical sensors capable of simultaneous measuring temperature and strain are of considerable interest due to their potential applications. Different configurations of Hi-Bi fiber Sagnac loops were reported to discriminate temperature and strain, such as using two different Hi-Bi fiber Sagnac loops concatenated in series [6], a fiber Bragg grating combined with a Hi-Bi fiber loop mirror [7], two different types of Hi-Bi fibers [8], and a long period grating combined with a section of Hi-Bi fiber [9]. Frazão [10] has also proposed a sensor head with a section of Hi-Bi erbium-doped fiber (EDF), and Han [11] has used Hi-Bi fiber incorporating an EDF to simultaneously measure temperature and strain. However, character-1 shaped polarization-maintaining fiber (PMF) based Sagnac loop for temperature and strain discrimination has not been reported.

In this letter, we present and demonstrate a configuration suitable for temperature and strain discrimination. Two character-1 shaped PMF based Sagnac loops are connected in parallel by a wavelength selected switch (WSS), and serve as sensor head. Due to the different sensitivities of the two Sagnac loops to temperature and strain, it is feasible for the proposed configuration to be used in discrimination of temperature and stain.

2. Experimental setup and operation principle

Fig. 1 presents the experimental setup for discrimination of temperature and strain by using two high birefringence Sagnac loops based on character-1 shaped PMF. The configuration consists of an optical broadband source, a liquid crystal based WSS, an optical fiber combiner, and two Sagnac loops containing two sections of character-1 shaped PMFs. An optical spectrum analyzer (OSA) with a resolution of 0.07 nm is used to monitor the output spectrum. The optical broadband source is an erbium-doped fiber laser source with a wavelength range of 100 nm, and central wavelength of 1550 nm. The inset is the photograph of cross section of the character-1 shaped PMF.

The Hi-Bi Sagnac loop is formed by a 3-dB optical coupler, an optical polarization controller (PC), and a section of character-1 shaped PMF. This character-1 shaped PMF is fabricated by the modified chemical vapor deposition technique. The stress-applied part looks like number “1”, so it is named character-1 shaped PMF. The character-1 shaped PMF produces highest birefringence with the least stress-applied part whose area is about 5% or less [12]. The first Sagnac loop contains 14 cm character-1 shaped PMF (PMF1), with the diameter of outer cladding is 125 μm. And another piece of character-1 shaped PMF (PMF2) with the length of 18 cm and outer cladding diameter of 80 μm is integrated into the second Sagnac loop.

The input light is launched into the liquid crystal based WSS, which split the input spectrum into two wavelength bands. Then, the two light signals with different wavelength bands are transmitted to two Sagnac loops, respectively. The Sagnac loop acts like a

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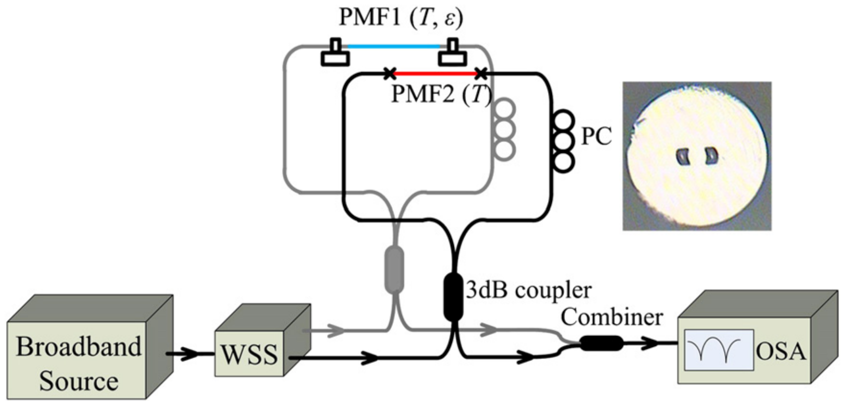

Fig. 1. Experimental setup of the proposed fiber sensor by using two sagnac loops connected in parallel. ×: the spliced point.

bandpass filter for the input light. The input light is split by the 3-dB coupler into two counter-propagating signals. The counter-propagating signals recombine at the coupler and exhibit interference due to the phase difference. And the phase difference is $\varphi = 2\pi BL/\lambda$, where L is the length of the PMF, λ is the operating wavelength, and B is the birefringence of the PMF. The transmission spectrum of Hi-Bi Sagnac loop is approximately a periodic function with respect to wavelength. The wavelength spacing $\Delta\lambda$ between the transmission dips is given by [13]

$$\Delta\lambda = \frac{\lambda^2}{BL}. \tag{1}$$

The PMF1 in the first Sagnac loop is applied both by temperature and strain. While for the second Sagnac loop, the PMF2 is isolated from strain. The PMF1 is fixed on translation stages with a resolution of 10 μm. Both the PMF1 and PMF2 are placed in a heating oven with the temperature resolution of 0.1 °C. By adjusting PC states of the two Sagnac loops, only one transmission dip for every Sagnac loop is observed in the corresponding wavelength range assigned by the WSS.

When strain or ambient temperature change, the birefringence and the fiber length of the character-1 shaped PMF will change, therefore the resonance wavelength of the transmission spectrum will change. According to [3], the Hi-Bi Sagnac loop presents positive strain sensitivity and negative temperature sensitivity. Discrimination between temperature and strain can be achieved by monitoring the wavelength variations of the two transmission dips of the Sagnac loops.

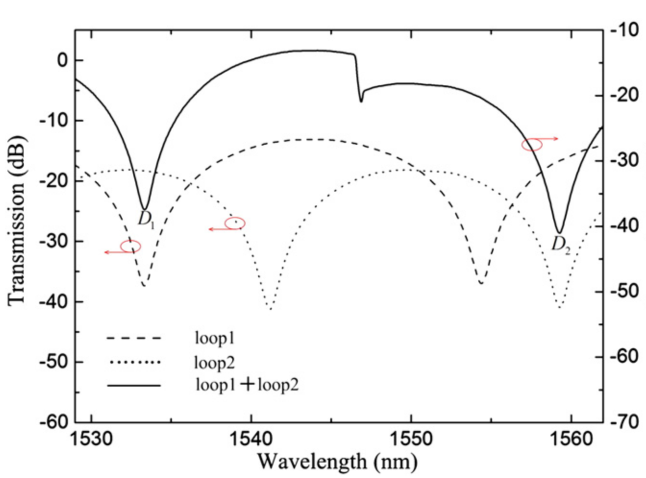

Fig. 2. Transmission spectra of the character-1 shaped PMF-based sagnac loop1 (dashed line), sagnac loop2 (dotted line), and sagnac loop1 connecting with sagnac loop2 (solid line).

3. Experimental results and discussion

The transmission spectra of the character-1 shaped PMF-based Sagnac loops at temperature of 20 °C are shown in Fig. 2. The solid line is the transmission spectrum of the two Sagnac loops which are connected in parallel by the liquid crystal-based WSS. The extinction ratio is about 24 dB, and the transmission dips D_1 and D_2 can be tunable in the range of 1528–1565 nm by tuning the two PCs which are inserted inside the two Sagnac loops. The input spectrum is divided into two parts: 1525–1547 nm, and 1547–1568 nm. In the measurement process, the spectrum range of each loop can be dynamically assigned by the WSS due to different environments, which makes the sensor more flexible.

We first measure the strain response of the two transmission dips D_1 and D_2 due to the applied strain from zero up to 714 με under the room temperature of 20 °C, as plotted in Fig. 3. $\Delta\lambda$ is the wavelength variation of the transmission dips due to the change of strain or temperature. It can be seen that the wavelength shift shows positive response to the change of strain. Fig. 4 shows the temperature response of the transmission dips by increasing the temperature from 26.3 °C to 56.9 °C with zero strain. The temperature response of the two transmission dips are different but in the same direction. Compared to strain response, the temperature responses of transmission dip are in the opposite directions. Figs. 3 and 4 indicate that the wavelength shift of the two transmission dips is almost linear with the variation of temperature and strain.

The wavelength shift can be simultaneously disturbed by strain and temperature according to $\Delta\lambda_i = K_{\varepsilon Di}\,\Delta\varepsilon + K_{TDi}\,\Delta T$, where $\Delta\varepsilon$ and ΔT are strain and temperature variation, respectively. And $i = 1, 2$ corresponds to the transmission dips D_1 and D_2. Then, discrimination

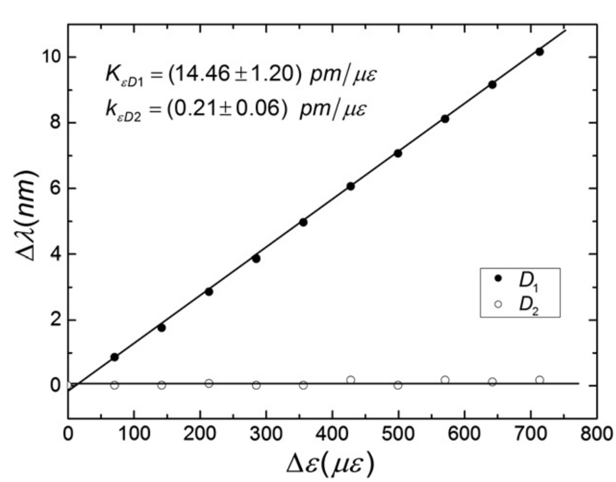

Fig. 3. Strain response of the proposed sensing head.

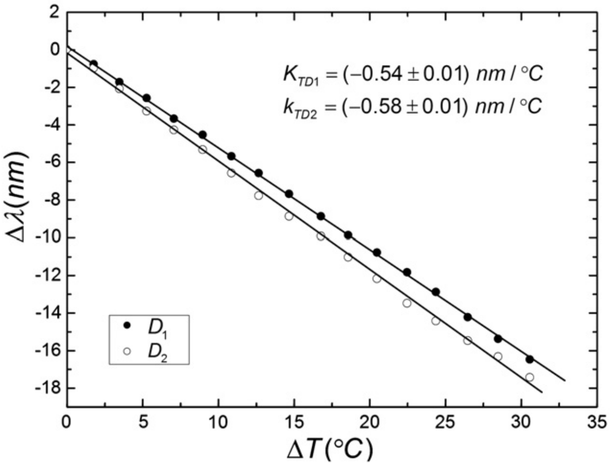

Fig. 4. Temperature response of the proposed sensing head.

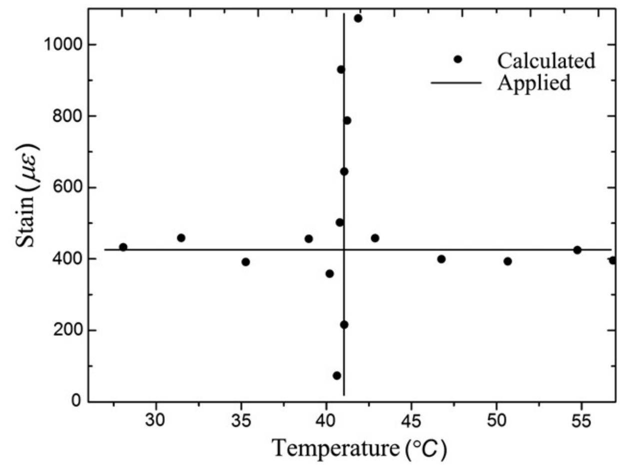

Fig. 5. Sensor output obtained by Eq. (3) when the temperature changed at a constant stain of 428 με and the applied strain varied with a fixed temperature of 41 °C.

between strain and temperature can be achieved by the following matrix:

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \frac{1}{M} \begin{bmatrix} K_{TD2} & -K_{TD1} \\ -K_{\varepsilon D2} & K_{\varepsilon D1} \end{bmatrix} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix} \tag{2}$$

where $K_{\varepsilon D1}$ and $K_{\varepsilon D2}$ are strain and temperature sensitivity coefficients, and K_{TD1} and K_{TD2} are temperature sensitivity coefficients. $M = K_{\varepsilon D1}K_{TD2} - K_{TD1}K_{\varepsilon D2}$. The temperature sensitivity coefficients (K_{TD1}, K_{TD2}) and the strain sensitivity coefficients ($K_{\varepsilon D1}$, $K_{\varepsilon D2}$) can be obtained by the experimental slopes shown in Figs. 3 and 4, resulting in:

$$\begin{bmatrix} \Delta\varepsilon \\ \Delta T \end{bmatrix} = \frac{1}{-0.0080} \begin{bmatrix} -0.58 & 0.54 \\ -0.00021 & 0.014 \end{bmatrix} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix} \tag{3}$$

where the units for $\Delta\varepsilon$, ΔT, and $\Delta\lambda$ are με (microstrain), °C and nanometer, respectively.

We also experimentally investigated the performance of the proposed sensor by simultaneous measuring temperature and strain, as shown in Fig. 5. Firstly, the sensor was applied by strain varying from zero to 1070 με, while the temperature was fixed at 41 °C. Then the second set of data was obtained by increasing temperature from 26 °C to 57 °C under the constant strain of 428 με. Eq. (3) was used to get the applied temperature and strain values. From Fig. 5, the maximum errors of strain and temperature were found to be 35 με and 0.8 °C, respectively.

4. Conclusion

In conclusion, we have proposed and experimentally demonstrated a fiber sensor for discrimination of temperature and strain. The sensor setup is composed of two Hi-Bi fiber Sagnac loops concatenated in parallel by a liquid crystal WSS. The two Hi-Bi fibers utilized are character-1 shaped PMF, and serve as sensor head. The sensitivities of strain and temperature are 14.46 pm and −0.54 nm, respectively. The maximum errors for strain and temperature are measured to be ±35 με and ±0.8 °C, which can be future enhanced by using other high accurate devices. The sensor configuration is simple and easy to manufacture. In addition, the sensor configuration can also be adapted to discriminate other different physical parameters, such as pressure and torsion. So it has great potential to be used in different applications.

Acknowledgments

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