Strain Sensor Realized by Using Low-Birefringence Photonic-Crystal-Fiber-Based Sagnac Loop

Huaping Gong, *Member, IEEE*, Chi Chiu Chan, *Member, IEEE*, Lihan Chen, and Xinyong Dong

***Abstract*—An optical fiber strain sensor by using a low-birefringence photonic crystal fiber (PCF)-based Sagnac loop is demonstrated. A fiber Sagnac loop is formed by the low-birefringence PCF of about 40 cm, and a section of about 140-mm PCF is used as the strain sensing element. The output spectra of Sagnac loop under different strain levels are measured and analyzed. The sensitivity of the strain measurement of -0.457 pm/$\mu\varepsilon$ is achieved within the range of 0–2520 $\mu\varepsilon$. The temperature effect is also analyzed.**

***Index Terms*—Fiber Sagnac loop, optical fiber sensor, photonic crystal fiber (PCF), strain sensor.**

I. Introduction

OPTICAL fiber sensors have been developed in different sensing applications due to their significant advantages, for example, accuracy, compactness, low cost, and immunity to electromagnetic waves. Sagnac fiber loop is a kind of optical fiber sensor, which just consists of a fiber coupler and a section of optical fiber, and it can be used to measure many parameters, such as strain, temperature, liquid level, and curvature [1]–[4]. By adopting different kinds of fibers, the sensing characteristics of the Sagnac fiber loop are varied [5]. In recent years, the polarization-maintaining photonic crystal fiber (PM-PCF)-based Sagnac loop has attracted much interest [6], [7]. A temperature-independent strain sensor by a highly birefringent PCF-based Sagnac interferometer has also been presented [8], and a pressure sensor with PM-PCF-based Sagnac interferometer has been proposed [9]. An elliptical hollow-core photonic bandgap fiber based on Sagnac configuration with a strain sensitivity of -0.81 pm/$\mu\varepsilon$ has been presented, and the birefringence of the fiber was measured to be 3×10^{-3} [10]. However, all of them used polarization-maintaining fiber (PMF) or high birefringence (Hi-Bi) fiber inserted into Sagnac fiber loop, while low-birefringence PCF-based Sagnac interferometer has not been presented.

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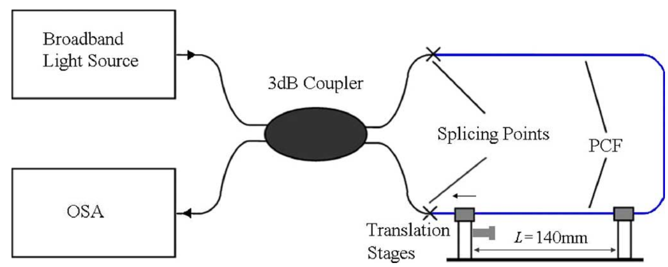

Fig. 1. Experimental setup of the strain measurement by using low-birefringence PCF-based Sagnac loop. (PCF: photonic crystal fiber; OSA: optical spectrum analyzer.)

In this letter, a low-birefringence PCF-based Sagnac loop employed as a strain sensor is proposed. Due to the low birefringence, just one dip in the wavelength range of 1500–1600 nm appears. The experimental setup and principle are described in Section II. The results and discussion are presented in Section III and a conclusion is given in Section IV.

II. Experimental Setup and Working Principle

The experimental setup of the strain sensor by the use of the low-birefringence PCF-based Sagnac loop is shown in Fig. 1. It includes a 3-dB single-mode-fiber (SMF) coupler and a 40-cm-long PCF (NL-1550-NEG-1, Crystal Fiber A/S). The mode field diameter of the PCF is about 2.8 μm, with seven rings of air holes in the cladding, and an attenuation coefficient in the wavelength range of 1510–1620 nm is less than 9 dB/km. The Sagnac loop was formed by splicing the two ends of the PCF to the arms of the 3-dB SMF coupler. The combined loss of these two splicing points was measured to be about $6 \sim 7$ dB, which was high due to the mode-field mismatch [11]. A broadband light source was connected to the input of the Sagnac loop, and the output spectrum was observed with an optical spectrum analyzer [(OSA) AQ6370, Yokogawa co., Ltd.].

The input light was split by the 3-dB SMF coupler and two counterpropagating light beams were propagated inside the Sagnac loop. When they passed through the PCF and encountered at the same coupler, the counterpropagating light beams introduced the relative phase difference due to the birefringence property of the PCF. So it led to the minima (dips) and maxima (peaks) in the output spectrum. The transmission spectrum of the Sagnac loop is approximately a periodic function of the wavelength [12]

$$T = \frac{[1 - \cos(\psi)]}{2} \quad (1)$$

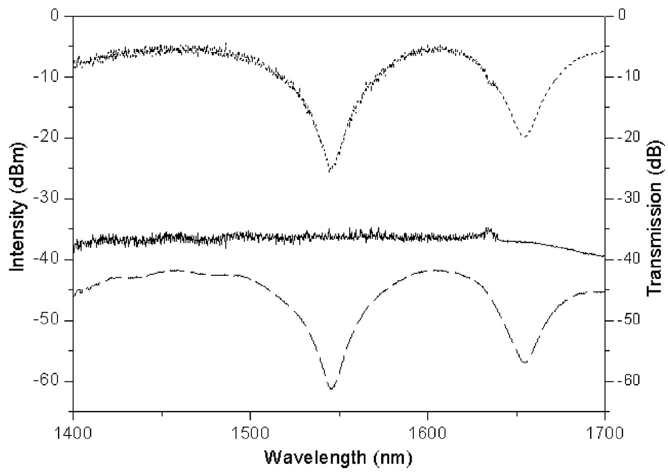

Fig. 2. Spectra of input supercontinuum light (solid line), Sagnac output (dashed line), and the normalized transmission (dotted line).

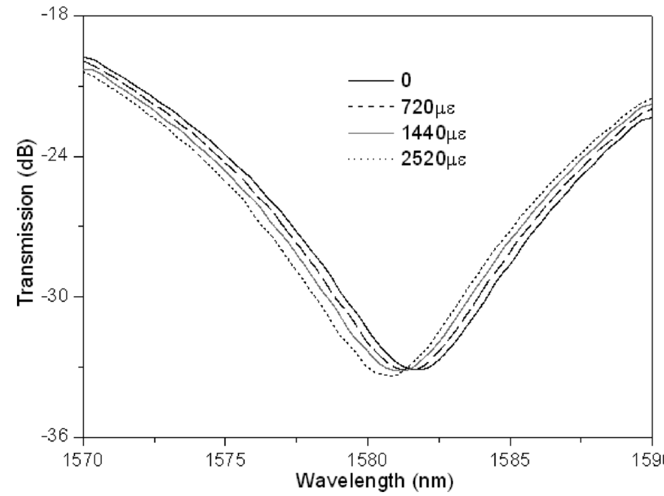

Fig. 3. Transmission spectra of Sagnac loop under different strain.

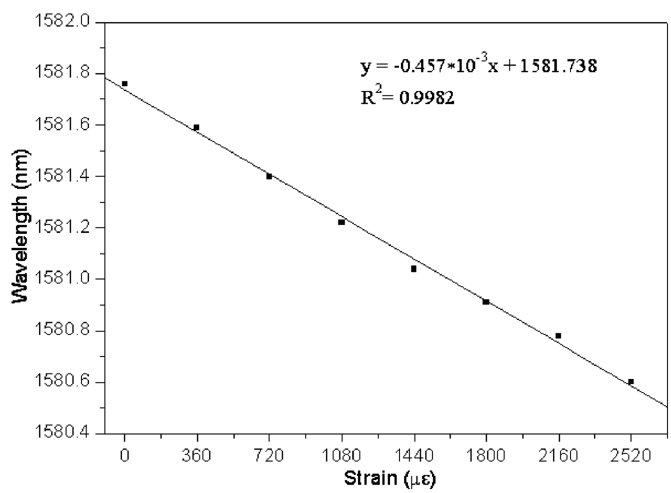

Fig. 4. Wavelength shift of the transmission dip versus strain. (Experimental data: square point; linear fit: line.)

where $\psi = 2\pi L_0 B/\lambda$ is the phase difference; λ is the operating wavelength; L_0 is the length of the PCF; and B is the birefringence of the PCF. The wavelength spacing (S) between the adjacent transmission dips or peaks is given by [8]

$$S = \frac{\lambda^2}{(B \cdot L_0)}. \tag{2}$$

A section of PCF is fixed straightly on translation stages with 140-mm separation, employing as sensing element, and the length of the sensing PCF is denoted as L. When the sensing PCF was stretched by moving one of the translation stages, the strain applied on the sensing PCF was varied, which introduced an elongation ΔL (a strain $\varepsilon = \Delta L/L$) and led to the change of phase difference ($\Delta\psi$)

$$\Delta\psi = \frac{2\pi}{\lambda}(\Delta L B + L\Delta B) \tag{3}$$

where ΔB is the variation of birefringence of the PCF caused by photoelastic effect. Then the wavelength of the dip or peak in the Sagnac output spectrum is changed by $\Delta\lambda = S\Delta\psi/2\pi$. So the change of the strain can be obtained by measuring the wavelength shift of the dip or peak in the output spectrum.

III. Experimental Resutls and Discussion

The transmission spectrum of the low-birefringence PCF-based Sagnac loop at room temperature of about 25 °C is shown in Fig. 2. Only one dip appears in the spectral range of 1500–1600 nm. The extinction ratio is about 21 dB, and the wavelength of this dip can be tunable in the range of 1500–1600 nm by tuning a polarization controller which is inserted inside the Sagnac loop. Therefore, this characteristic could be used as a bandstop filter for the C- and L-band. It can be seen from (2) that S will become large when the product of B and L is very small. Thus only one dip appears in the wavelength range of 1500–1600 nm. A broadband, supercontinuum light source (SuperK Compact, Koheras A/S) was used in the experiment. In Fig. 2, two dips appear in the spectral range of 1400–1700 nm, and the wavelength spacing between the two adjacent dips is about 110 nm. The birefringence value of 5.8×10^{-5} was estimated by (2), which is about one or two orders less than that of PM-PCF or high-birefringence fiber (the order of 10^{-4}–10^{-3}).

When the applied strain was varied from 0 to 2520 $\mu\varepsilon$ by increasing the separation distance between the two stages, the Sagnac output spectra under different strain levels are shown in Fig. 3. The wavelength of the dip in the Sagnac transmission spectrum was changed from 1581.76 to 1580.6 nm, corresponding to a total wavelength shift of about 1.16 nm. The wavelength shift of the transmission dip as a function of strain change is shown in Fig. 4. As can be seen, the wavelength shift of the dip has a linear relationship with the strain change, and a sensitivity of about -0.457 pm$/\mu\varepsilon$ was achieved. This strain sensitivity is two times higher than that of the reported PM-PCF-based Sagnac interferometer [12]. But the resolution of strain measurement is limited by the 40-pm wavelength error due to the flat-profile dip, which is calculated to about 87 $\mu\varepsilon$. The Hi-Bi fiber-based Sagnac sensor had a small fringe separation, which could lead to the overlap of the fringes when the wavelength shift is larger than the fringe separation [8]. By comparison, our

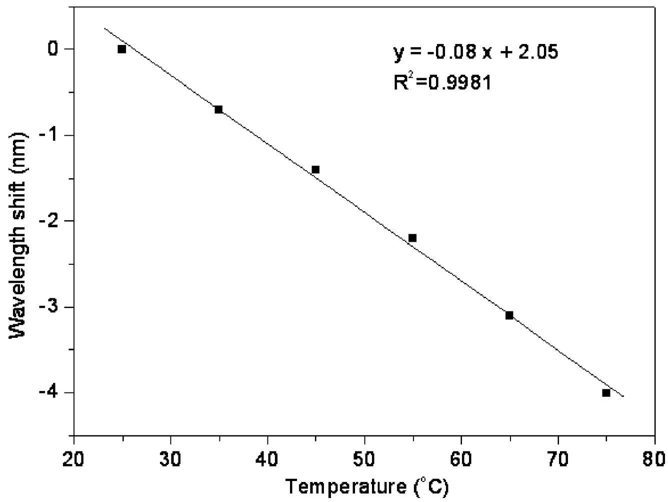

Fig. 5. Wavelength shift of the transmission dip versus temperature. (Experimental data: square point; linear fit: line.)

proposed sensor has a potential ability to acquire larger measurement range due to the wider fringe spacing.

The influence of temperature on the Sagnac loop was also investigated. The 40-cm PCF was placed on the temperature-controlled oven which was set to increase from 25 °C to 75 °C with a step of 10 °C. The wavelength shift versus temperature is shown in Fig. 5. It shows that the wavelength shift has a linear relationship with the temperature. A temperature sensitivity of about -80 pm/°C was achieved. So the cross sensitivity of the temperature on the strain is about 175 $\mu\varepsilon$/°C. But the strain experiment was performed in a temperature-controlled environment, and the temperature variation was less than 0.1 °C, so the error of strain measurement induced by temperature is just about 17.5 $\mu\varepsilon$. Moreover, the temperature effect on the proposed strain sensor could be compensated by placing a fiber Bragg grating or a long-period grating outside the Sagnac loop, which can be realized easily [13].

IV. Conclusion

A fiber Sagnac loop-based strain sensor has been demonstrated by using the low-birefringence PCF. Compared to other PM-PCF and Hi-Bi PCF-based Sagnac loops, our proposed Sagnac loop has comparable strain sensitivity, and has a potential ability to acquire larger measurement range due to the wider fringe spacing. It is also suitable to be used as a filter in the C- and L-band. The sensitivity of the strain measurement of about -0.457 pm/$\mu\varepsilon$ is achieved within the range of 0–2520 $\mu\varepsilon$. The strain resolution can be further enhanced by using another high accurate demodulation method. Moreover, wavelength dip in the transmission spectrum of the Sagnac loop can be changed by tuning a polarization controller which is inserted inside the Sagnac loop. It is simple, easy to fabricate, and sensitive to many parameters, so it shows a great potential for many sensing applications.

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