Temperature-insensitive strain sensor with polarization-maintaining photonic crystal fiber based Sagnac interferometer

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A fiber-optic strain sensor is demonstrated by using a short length of polarization-maintaining photonic crystal fiber (PM-PCF) as the sensing element inserted in a Sagnac loop interferometer. Spectrum shift in response of strain with a sensitivity of 0.23 pm/$\mu\varepsilon$ is achieved, and the measurement range, by stretching the PM-PCF only, is up to 32 mε. Due to the ultralow thermal sensitivity of the PM-PCF, the proposed strain sensor is inherently insensitive to temperature, eliminating the requirement for temperature compensation. [DOI: 10.1063/1.2722058]

Optical fiber Sagnac interferometers (OFSIs) have been widely studied and applied in gyroscopes and other sensor applications for many years.[1,2] Some of them used polarization-maintaining (or highly birefringent) fibers (PMFs) to introduce optical path difference and cause interference between the two counterpropagating waves in the Sagnac loop and used them as sensing elements.[3–6] Because the boron-doped stress-applying parts in such fibers (e.g., Panda and bow-tie PMFs) have much higher thermal expansion coefficient than the cladding (normally pure silica), their birefringence is quite sensitive to temperature. Temperature sensors based on OFSIs showed a high sensitivity of 0.99 nm/°C, which is about one and two orders magnitude higher than that of a long-period fiber grating (LPG) and fiber Bragg grating sensors.[3,4] Strain sensors based on the strain-induced variation in birefringence of the PMFs used in OFSIs were also proposed and characterized.[5,6] These sensors possess lots of advantages including simple design, easy to manufacture, high sensitivity, and low cost. However, previously reported OFSI sensors are all based on conventional PMFs whose birefringence is dependent on temperature. When they are used for sensing other measurands such as strain, the high thermal response of conventional PMFs may cause serious cross-sensitivity effects and reduce the measurement accuracy. Simultaneous measurement of strain and temperature was realized by incorporating an OFSI with an LPG,[7] but the reported strain measurement range was small, about 700 $\mu\varepsilon$, possibly caused by the fusion splicing between different fibers, which may greatly weaken the fiber strength. Furthermore, LPGs are generally very sensitive to fiber bending which may limit the sensor applications.

In recent years, PMF based on photonic crystal fiber (PCF) technology, i.e., PM-PCF, has been commercially available and attracted lots of research interest. Due to the pure-silica (and air holes) design of the fiber itself, the thermal dependence of PM-PCF is very low. OFSIs based on PM-PCFs are therefore very stable with respect to temperature. Previous reports showed 55–164 times less thermal sensitivities of PM-PCF based OFSIs than conventional PMF based OFSIs.[8,9] The absolute peak wavelength shift in response to temperature can be as small as 0.3 pm/°C, which can be totally neglected for sensors in common environments without very large temperature variations. Therefore, OFSI strain sensors with a very low or negligible thermal sensitivity are expected by using pure-silica based PM-PCFs. Furthermore, attributed to the flexible fabrication design of PM-PCFs, birefringence can be much higher than that of conventional PMFs.[10] This will greatly reduce the required PMF length and benefit the sensors from a size-reduced sensing element (i.e., the PM-PCF). In this letter, a Sagnac interferometer strain sensor has been demonstrated by using a short length of PM-PCF incorporating with a 3 dB single-mode fiber coupler and a 1550 nm broadband light source. Spectrum shift in response of strain is theoretically analyzed and a simplified description is given out. Strain measurement with a sensitivity of 0.23 pm/$\mu\varepsilon$ is achieved, and the measurement range, by stretching the PM-PCF only, is up to 32 mε. The strain measurement is inherently temperature insensitive due to the great thermal stability of PM-PCF based Sagnac interferometers. That improves the accuracy of strain measurement and eliminates the requirement for temperature compensation.

The proposed Sagnac interferometer strain sensor, as shown in Fig. 1, consists of a 3 dB fiber coupler with con-

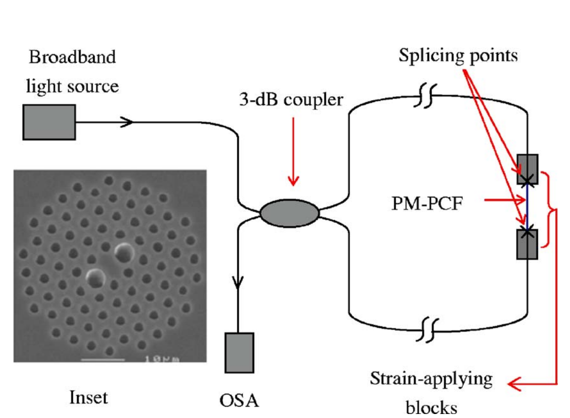

FIG. 1. (Color online) Schematic diagram of the proposed OFSI strain sensor. Inset: SEM of the cross section of the PM-PCF.

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ventional single-mode fiber and a short length of PM-PCF. The 3 dB coupler splits the input optical light equally into two counterpropagating waves. Interference will happen when they recombine at the coupler because of the relative phase difference introduced to the two orthogonal guided modes by the PM-PCF. Ignoring the insertion losses of the Sagnac loop, transmission ratio of optical intensity injected into the OFSI in terms of phase difference can be described as

$$T=[1-\cos(\psi)]/2, \tag{1}$$

where $\psi=2\pi LB/\lambda$ is the phase difference, λ is the wavelength, L is the length of the PM-PCF, $B=n_s-n_f$ is the birefringence of the PM-PCF, and n_s and n_f are effective refractive indices of the PM-PCF at the slow and fast axis, respectively. T is approximately a periodic function of wavelength with a spacing between adjacent transmission peaks of $S=\lambda^2/(BL)$. The phase change $\Delta\psi$ induced by an elongation ΔL (i.e., a strain $\varepsilon=\Delta L/L$) to the PM-PCF can be given approximately by

$$\Delta\psi=\frac{2\pi}{\lambda}[\Delta LB+L\Delta B], \tag{2}$$

where $\Delta B=\Delta n_s-\Delta n_f$, is the variation of birefringence of the PM-PCF caused by photoelastic effect. Based on the analysis of photoelastic effect in single-mode fibers,[11] the change of effective refractive index in the fiber core is related to the applied strain with a coefficient named effective photoelastic constant. It is therefore assumed that Δn_s and Δn_f have similar descriptions but different effective photoelastic constants, expressed as follows:

$$\Delta n_s=p_e^s n_s\varepsilon \tag{3a}$$

$$\Delta n_f=p_e^f n_f\varepsilon, \tag{3b}$$

where p_e^s and p_e^f are the effective photoelastic constant for the slow and fast axes, respectively. By substituting Eqs. (3a) and (3b) into Eq. (2) and considering the relationship between spectrum (or peak wavelength) shift and phase change, i.e., $\Delta\lambda=S\Delta\psi/(2\pi)$, the following relationship can be obtained:

$$\Delta\lambda=\lambda(1+p_e')\varepsilon, \tag{4}$$

where $p_e'=(n_f p_e^f-n_s p_e^s)/B$, is a constant that describes the strain-induced variation of the birefringence of the PM-PCF. From Eq. (4), it can be seen that $\Delta\lambda$ is directly proportional to ε; therefore, linear spectrum (or peak wavelength) shift is expected with change of the applied strain.

In our experiment we used an 86 mm long PM-PCF (manufactured by Blaze-Photonics). The PM-PCF has a noncircular core surrounded by air holes with different diameters along the two orthogonal axes. The scanning electron micrograph (SEM) of the cross section of the PM-PCF is shown as the inset of Fig. 1. Mode field diameters at two orthogonal polarizations are 3.6 and 3.1 μm, respectively, and the group birefringence at 1550 nm is $\sim 8.7\times10^{-4}$. The two ends of the PM-PCF were connected to the two ports of the 3 dB coupler by using a normal arc fusion splicer. The total loss of the two splicing points is ~6 dB, which is relatively large due to mismatching of mode field and numerical apertures between single-mode fiber and PM-PCF. It is noted that the insertion loss due to splicing can be reduced by further optimization of the splicing conditions (such as the arc power and duration, distance between fiber ends, etc.). However, a relatively high insertion loss doesn't affect the accuracy of our measurement since what we measured for the sensor output is spectrum (or wavelength) shift, though the peak optical power of the sensor output is reduced. A broadband amplified spontaneous emission source with pumped erbium-doped fiber centered at 1550 nm was used as the light source. The transmission spectrum of the OFSI sensor was measured by using an optical spectrum analyzer (OSA) with wavelength resolution of 10 pm.

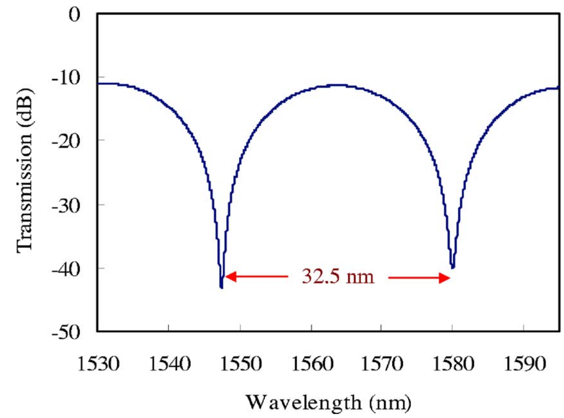

FIG. 2. (Color online) Transmission spectrum of the PM-PCF Sagnac interferometer.

Figure 2 shows the transmission spectrum of the PM-PCF based Sagnac interferometer within a wide wavelength range of 70 nm. The wavelength spacing between the two transmission minima is ~32.5 nm, and a good extinction ratio of 32 dB was achieved at the first transmission minimum located at 1547 nm. Since the light source we used is not polarized and there is no polarization-dependent element used in the sensor system, the stability of the sensor output against environmental variations, such as small vibrations, is good.

We fixed one end of the PM-PCF and stretched the other end by using a precision translation stage. Figure 3 shows several measured transmission spectra around the transmission minimum at 1547 nm under different applied strains. The spectrum shifted ~7.5 nm to the longer wavelength direction when the strain was increased from 0 to 32 mε. The measured data are shown in Fig. 4. A linear fitting to the

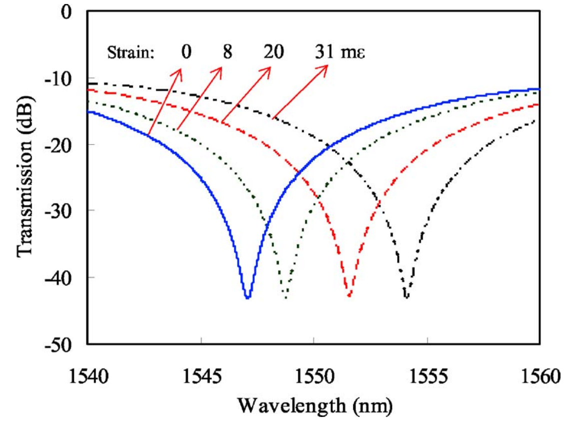

FIG. 3. (Color online) Measured transmission spectra under different strains.

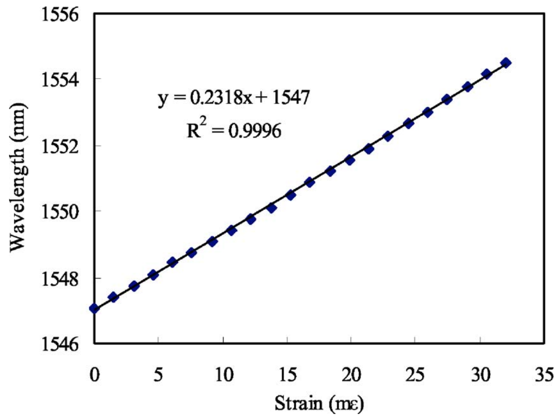

FIG. 4. (Color online) Wavelength shift of the transmission minimum at 1547 nm against the applied strain.

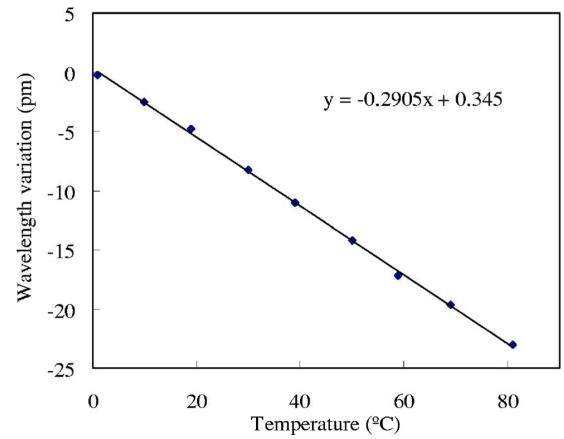

FIG. 5. (Color online) Wavelength variation of the transmission minimum at 1547 nm against temperature.

experimental data gives a wavelength-strain sensitivity of 0.23 pm/$\mu\varepsilon$ and a high R^2 value of 0.9996, which shows that the linearity of the wavelength to strain response is excellent. Therefore, the experimental data agree well with the theoretical prediction, and the constant p_e' in Eq. (4), calculated from the wavelength-strain sensitivity value, is −0.82.

The resolution of the strain measurement, limited by the 10 pm wavelength resolution of the used OSA, is ~43 $\mu\varepsilon$, which is actually quite high when taking into account the large measurement range. The maximum value of the applied strain is mostly determined by the maximum strain that the PM-PCF can endure, not the strength of the fusion splicing points because the two splicing points between the PM-PCF and single-mode fibers were prevented from being stretched as they were glued to the strain-applying blocks. As a result, the measurement range is several times larger than that of fiber Bragg grating and long-period grating sensors, where the fiber strength is significantly weaken during the grating inscription by high power ultraviolet laser beams.[12] This may be regarded as one of the several advantages of the proposed PM-PCF based OFSI strain sensor over the two kinds of fiber grating sensors.

Temperature stability of the Sagnac interferometer strain sensor was also tested by setting the sensor head into a temperature-controlled container. The transmission minimum at 1547 nm was moved to shorter wavelength by only 22 pm when the temperature was increased up to 80 °C. Measurement results are shown in Fig. 5. The temperature sensitivity is only 0.29 pm/°C, which, compared with the reported value of 0.99 nm/°C of the OFSI temperature sensor based on conventional PMF,[3] is about 3 000 times lower. The temperature sensitivity is also in good agreement with the previously reported value in Ref. 8 where the same PM-PCF was used. If a temperature variation of 30 °C is assumed, the corresponding wavelength shift of the strain sensor is only 8.7 pm, which is even smaller than the wavelength resolution of the OSA. Therefore, such a low temperature sensitivity can be totally neglected when the sensor is operated in normal environmental condition without very large temperature variations.

In conclusion, we have proposed and demonstrated a fiber Sagnac interferometer strain sensor by using a short length of PM-PCF as the sensing element. A simplified description of the spectrum shift in response of strain has been derived and a sensor setup with a sensitivity of 0.23 pm/$\mu\varepsilon$ has been demonstrated. Compared with the conventional PMF based OFSI sensors and fiber Bragg grating or long-period grating sensors, the proposed strain sensor is inherently insensitive to temperature, eliminating the requirement for temperature compensation. It is also simple, easy to manufacture, potentially low cost, and possesses a much larger measurement range.

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