Sensitivity characteristics of high-birefringence Sagnac interferometer sensors

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ABSTRACT

The sensitivity characteristics of the sensors based on high-birefringence Sagnac interferometer are theoretically analyzed and experimentally verified. We analyze the sensitivity of the sensor in terms of the frequency instead of the wavelength of the light and the sensitivity can be improved by reducing the length of high birefringence fiber. The strain sensing experiments are carried out and the experimental results agree well with the theoretical analysis.
Keywords: Optical fiber Sagnac interferometer, high birefringence fiber, strain sensor

1. INTRODUCTION

Optical fiber Sagnac interferometer (OFSI) is one of the most attractive and common used fiber devices in fiber communication and sensors owing to its simple structure, ease of fabrication and flexible applications [1-9]. Especially, the OFSIs based on high-birefringence fiber (HBF) are widely studied as sensors for various physical parameter measurements such as strain, temperature, curvature, twist, pressure, refractive index and so on [2, 4-8]. In these studies, great efforts are focused on the goal of improving the sensitivities of the sensors. For example, sensitivities of OFSIs incorporating of diverse HBFs like panda fiber, elliptical core fiber, elliptical cladding fiber, bow-tie fiber and D-type fiber were compared [6]; Special treating processes such as chemical etching, tampering and side-polishing were also applied to the HBF to improve the sensitivities [6]; Recent years, high-birefringence photonic crystal fibers (HB-PCFs) as well as liquid-filling induced HB-PCF were employed in the OFSIs [2, 7]; Besides, fiber gratings including fiber Bragg grating, long period grating and chirped grating were introduced into the OFSI, too. On the one hand, these methods are more or less complex and the special fibers used are not common employed. On the other hand, an important and basic characteristic about the effect of the length of high-birefringence fiber in Sagnac loop on the sensitivities of the sensor was overlooked. One tends to attribute the improved sensitivity to the specially designed HBF or tends to use longer HBF for achieving high sensitivity. However, we found it in our previous experiment that the length of HBF used in the OFSI was more crucial and essential influences on the sensitivity. In this work, sensitivity characteristics of the sensor based on OFSI are analyzed theoretically and experimentally demonstrated.

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2. SENSOR STRUCTURE AND WORKING PRINCIPLE

The typical configuration of an OFSI is shown in Fig. 1. A section of HBF is spliced with a 3-dB coupler to form a Sagnac loop. Two light beams split by the 3-dB coupler counterpropagate along the loop and then interfere when they meet at the coupler again. The transmission spectrum of the OFSI is given as [8]

$$T = (1 - \cos\varphi)/2 \tag{1}$$

where $\varphi = 2\pi BLf / c$ is the total phase; B and L are the birefringence and length of the HBF, respectively; c is the speed of light in vacuum, which is a constant; f is the frequency of the light. The frequency f is used in the equations instead of the wavelength in order to avoid the unnecessary approximation in the analysis. Eq.(1) shows that T is a sinusoidal function of f. If the condition $\varphi = 2m\pi$ (m is integer) is fulfilled, the frequency of the dips on the transmission spectrum are described as $f_m = mc/BL$, where m indicates the fringe orders of the interference spectrum. Therefore, the frequency space F between the adjacent dips is given as,

$$F = f_{m+1} - f_m = c/BL \tag{2}$$

From Eq.(2) we can draw the conclusion that shorter length of HBF leads to larger frequency space. The frequency space between the adjacent transmission dips is a constant, which is quite different from the result in terms of wavelength. If the birefringence of the HBF is changed due to the external measured physical parameters (e.g. strain, twist, temperature, etc) the transmission spectrum will change accordingly. Hence, the sensitivity of the sensor Δf can be given as,

$$\Delta f = f_m^{'} - f_m = mc\frac{\Delta B}{BB'L} \tag{3}$$

where B' is the birefringence after change, $\Delta B = B' - B$. Eq.(3) shows that the frequency change of the transmission spectrum Δf is inversely proportional to the length of HBF L. However, considering the conclusion from Eq.(2), if the length of the HBF is too small, the frequency space will be too large to exceed the spectrum range of the broad band light source, subsequently, no fringes can be observed. Therefore, on the condition that at least one transmission dip can be observed in the spectrum range of the light source, the length of HBF should be as short as possible in order to achieve higher sensitivity.

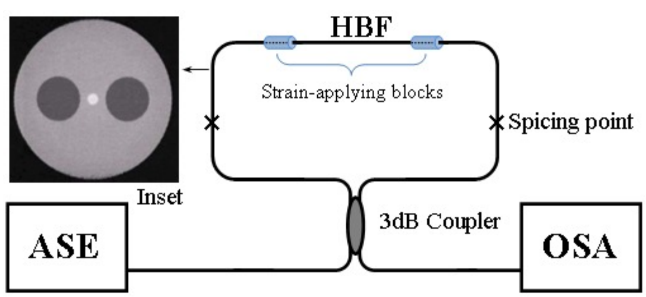

Fig.1 Scheme of OFSI based on high-birefringence fiber. Inset: cross section of panda fiber

3. RESULTS AND DISCUSSION

In order to verify the conclusion drawn from the theoretical analysis, 3 OFSIs with different HBF-lengths were fabricated and strain sensing experiments were carried out. The polarization maintaining fiber (PMF), panda fiber (PM-1550-HP), was used as HBF in the experiment, whose birefringence was 3.3×10^{-4}. The panda fiber is the most common used PMF and the image of the cross section is shown in Fig. 1. The lengths of the PMF fibers used in the 3 OFSIs were 6.5cm, 7.1cm and 52.2cm, respectively. A section of PMF in the Sagnac loop was removed coating and attached to two translation stages with a resolution of 0.01mm in order to apply strain on the PMF. The distance between the two fixing points was 5cm, which was the same for the 3 OFSIs. An amplified spontaneous emission (ASE, 1520-1620nm) source was employed as the broadband light source and the transmission spectra were observed by an optical spectrum analyzer (OSA).

The transmission spectra of the 3 OFSIs are showed in Fig.2. Their shapes are analogy, which are sinusoidal and their extinction ratios are about 30dB. The periods of the 3 transmission spectra are 58.52nm, 19.58nm and 8.89nm for the HBF-length of 52.2cm, 17.1cm and 6.5cm respectively. We can conclude from Fig.2 that the shorter the HBF length, the larger the period of the transmission spectrum. This result is in consistent with the theoretical analysis of Eq.(2).

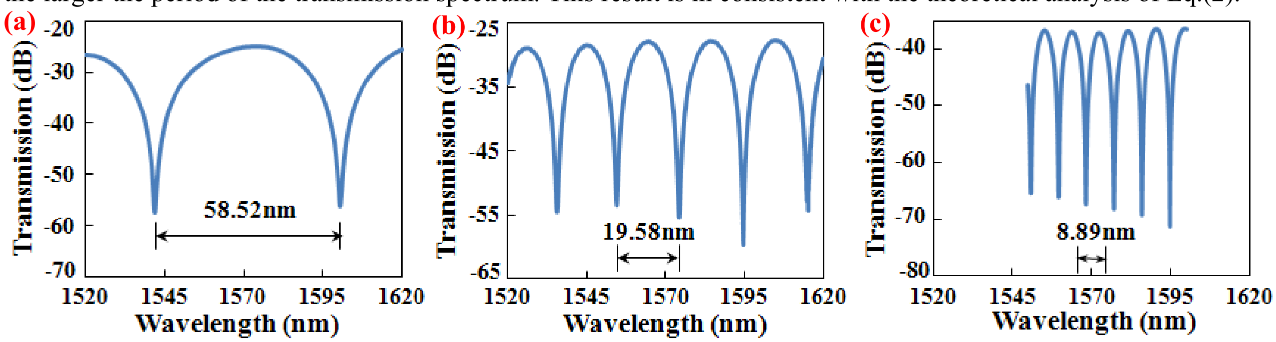

Fig.2 Transmission spectra of the OFSI sensors with different lengths of HBFs (a) 6.5cm (b) 17.1cm (c) 52.2cm

In order to estimate the sensitivity of the sensors, strain was applied on the HBF through the translation stages. In Fig.3, the sensor with HBF-length of 6.5cm was chosen as an example to show detailedly the variation trend of the transmission spectra as the strain increasing. The dip around 1542.00nm was shifted from 1526.16nm to 1618.74nm totally 92.58nm to the longer wavelength side as the strain increasing from 0mε to 4.8mε. Only one dip around 1542.00nm is plotted in Fig.3 so that the spectrum shift can be observed clearly. The dip wavelength of the transmission spectrum was measured and plotted in Fig.4. The linear fit method was applied to the results. The corresponding sensitivities of the strain sensors with HBF-lengths of 6.5cm, 17.1cm and 52.2cm were calculated to be 19.58pm/με, 6.408pm/με and 2.438 pm/με respectively with high R^2 values of 0.9992, 0.9992 and 0.9925, which show the sensors have an excellent linearity. The sensitivity of the sensor based on 6.5cm-length HBF is about 8 times higher than that of the sensor based on 52.2cm-length HBF. The sensitivity is approximately inversely proportional to the length of HBF used. Hence, we can conclude that the shorter the HBF length, the higher the sensitivity. The theoretical predication of Eq. (3) was well supported by the experimental results.

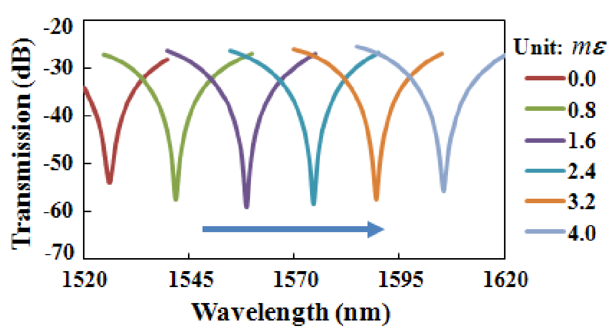

Fig.3 The variation trend of the transmission spectrum of the sensor with 6.5cm-length HBF verses the applied strain

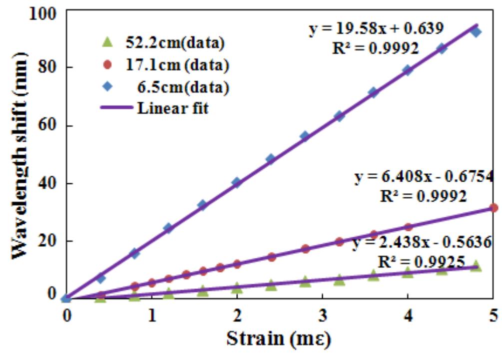

Fig. 4 The change of the dip wavelengths of the 3 sensors verses the applied strain

4. CONCLUSION

In a conclusion, a simple and basic method to improve the sensitivity of the sensor based on highly birefringent OFSI is proposed and experimentally demonstrated. The theoretical analysis predicts that the sensitivity of the sensor can be improved by reducing the length of HBFs used in the Sagnac loop. The results of strain sensing experiment support the analysis prediction. The achieved best sensitivity of the sensor by using 6.5-cm HBF is 19.58pm/με.

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