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Sensitivity dependence of fiber loop mirror on the length of high birefringence fiber

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ABSTRACT

A model of fiber loop mirror with the distinct concepts of sensing length and total length is established. The sensitivity dependence of fiber loop mirror on the sensing length and total length is discussed theoretically and experimentally. The sensor sensitivity showed being linearly dependent of the ratio of the sensing length and the total length. The experimental results well support the predications by the model.

1. Introduction

Thanks to the great advances in optical-fiber communication technologies, optical fiber Sagnac interferometer (OFSI) was first demonstrated more than 35 years ago [1]. At the beginning, OFSI was used in fiber optic gyroscope (FOG) systems to detect the rotation with respect to inertial system by means of Sagnac effect [2]. In order to guarantee the accuracy of rotation measurement, any type of non-reciprocity other than rotation should be avoided or reduced to a certain extent such as Faraday rotation, thermal effect, mechanical forces and so on. However, from a different perspective, these non-reciprocal phenomena also offered new opportunities for measuring these parameters. For example, temperature sensor based on OFSI was reported in 1997 [3]. Current sensor based on non-birefringent OFSI was proposed in 1988 [4]. Since then, more OFSI-based sensors or devices were presented parallel to the long inevitable development period of FOG [5–11]. Although this kind of sensors employs the same OFSI structures, their principle, which is modal interference, has nothing to do with Sagnac effect. In order to distinguish this kind of sensors from FOG for convenient description in the following discussion, we call it fiber loop mirror (FLM) sensors.

The significant distinctions between FOG and FLM sensors are their operating light modes and their ways to accumulate the optical phase difference (OPD). FOG systems operate on single polarization mode and the OPD is generated by Sagnac effect. This linearly polarized light is split into two light waves by the 3 dB polarization maintaining (PM) coupler. If the fiber loop of FOG is rotated, the light wave propagating along the same direction is some kind of "slower" and has to "chase" the rotation while the light wave couterpropagating is some kind of "faster", so the OPD between the two light waves occurs by means of the relativity theory. This OPD is proportional to the length of the polarization maintaining fiber (PMF) within the Sagnac loop. The typical length of PMF in a practical FOG system is around 1 km [12].

FLM sensors operate on two orthogonal polarization modes and the OPD is generated by means of birefringence effect. The non-polarized light is split into two light waves by a non-PM 3 dB coupler. Both of the couterpropagating light waves decompose into two orthogonal linearly polarized light wave components along the fast and slow axes respectively when they enter the high birefringence fiber (HBF), of which one component propagates faster than the other due to birefringence effect. The Sagnac loop serves to beat together the fast and slow components so that interference can be produced. The sensitivities of FLM sensors depend on the length of the HBF within the Sagnac loop, but the dependence relationship was not clearly elaborated in the literatures. Sometimes, even contradictory conclusions were reported. For example, some researchers tended to believe longer HBF length within the Sagnac loop gave a higher sensitivity [13,14]. Meanwhile, some researchers observed the phenomenon that the sensitivity was irrelative to the HBF length [15] while some researcher just assumed this

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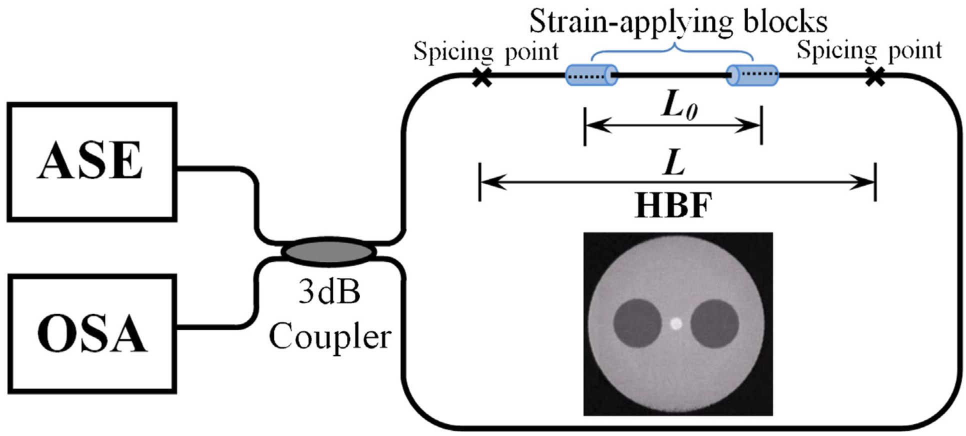

Fig. 1. Schematic diagram of the structure of FLM. Inset: the cross section of traditional PMF, pander fiber.

Table 1
Parameters chosen for the FLMs and their results.

FLM	L_0 (cm)	L (cm)	L_0/L	$\Delta\lambda$(pm/$\mu\varepsilon$)
A	4.9	6.5	0.75	19.580
B	4.7	17.1	0.27	6.408
C	5.1	52.2	0.10	2.438
D	2.0	50.0	0.04	1.021
E	10.2	50.5	0.20	5.476
F	47.6	50.7	0.94	25.305
G	4.3	4.7	0.87	22.530
H	9.3	9.7	0.96	26.407

conclusion [16]. In our previous work, we found that higher sensitivity can be obtained with shorter HBF length [17]. Nonetheless, in most of the works, the HBF lengths within the FLM sensors were just randomly chosen without clear guideline. One possible reason for these contradictory conclusions is that the sensitivity property of FLM sensors was confused with FOG. Another possible reason is that only part of the HBF within the Sagnac loop worked as the sensing element, which was very common among various FLM sensors [5,13,18]. For instance, Zhao demonstrated a curvature sensor with 100 cm PMF but only 14.2 cm was used as sensing element [14]. Kim proposed a temperature sensor by using PCF with 20 cm length infiltrated while the remaining 80 cm length unfilled [19]. Chen carried out a humidity sensor based on partly chemically etched HBF [20]. This partially involved HBF makes the conditions more complex.

In this work, we establish a model of FLM sensors and investigate the sensitivity dependency on the HBF length in order to clarify these confusions existing in the literatures.

2. Operating principle

A typical FLM is configured simply by splicing a section of HBF and a single mode fiber (SMF) 3 dB coupler to form a Sagnac loop, which is shown in Fig. 1. The whole length of the HBF is denoted as L, whilst partial length of the HBF functions as birefringence sensitive element for sensing measurement, which is denoted as L_0. An OPD is introduced between the two orthogonal polarization modes due to the birefringence of HBF. Hence, an approximately sinusoidal interference spectrum is produced as the two beams beat together again at the coupler, which is given by [5]

$$T = (1 - \cos\phi)/2 \quad (1)$$

where $\phi = 2\pi BL/\lambda$ is the OPD between the two orthogonal modes; where B and L are the birefringence and length of the HBF, respectively; λ is the wavelength of the light. If the condition $\phi = 2\pi m$ (m is an integer) is fulfilled, the transmission spectrum reaches its minimum. The wavelength of the m-th order fringe on the transmission spectrum can be given as

$$\lambda_m = BL/m \quad (2)$$

Hence, the period of the interference spectrum or the free spectral range (FSR) between the two adjacent transmission dips S can be given by

$$S = \lambda^2/BL \quad (3)$$

Eq. (3) shows that the FSR (S) is inversely proportional to L. Usually, the sensitivity of FLM sensors is described by spectrum shift or dip wavelength shift. By considering the relationship between the spectrum shift and OPD i.e. $\Delta\lambda = S\Delta\phi/2\pi$ and substituting Eq. (3) into this equation,

the sensitivity can be deduced as [10]

$$\Delta\lambda = \frac{\Delta B}{B}\frac{L_0}{L}\lambda \quad (4)$$

Eq. (4) shows both the sensing length (L_0) and the total length (L) contribute to the sensitivity. From Eq. (4) we can predict in some special cases: (i) If L = const, the sensitivity is proportional to the sensing length (L_0); (ii) If L_0 = const, the sensitivity is inversely proportional to the total HBF length (L); (iii) If $L = L_0$, which means the full length of HBF is used for sensing measurement, Eq. (4) becomes $\Delta\lambda = (\Delta B/B)\lambda$, which is the maximum sensitivity. Meanwhile, the sensitivity is independent on the HBF length (L).

3. Experimental results and discussion

In order to verify the above predictions, a series of FLM sensors with different sensing and total lengths of HBF were fabricated. The sensitivities of these sensors were measured by taking strain test. The HBF employed was traditional PMF, panda fiber (PM-1550-HP), whose cross section is shown in the inset in Fig. 1. The birefringence of the PMF was 3.3×10^{-4}. A section of PMF was