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RESEARCH ARTICLE

A new magnetic sensor with Mach-Zehnder/Sagnac optical fiber interferometer

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Abstract This paper presents a new structure for magnetic sensor with Mach-Zehnder/Sagnac optical fiber interferometer. The magnetostrictive optical fiber sensor is placed in one of the two arms of the Mach-Zehnder interferometer, which can detect the optic phase shift by testing the length difference of the arm caused by environmental magnetic field. Because of forward and backward transmission in the arms, the Mach-Zehnder/Sagnac optical fiber interferometer can deduce twice exactly of the phase shift proportional to the length difference as Mach-Zehnder interferometer. Theoretically, description of the Mach-Zehnder/Sagnac interferometer is given, and some main issues in the magnetic field sensor with optical fiber interferometer are demonstrated with experiments. The magnetic sensors are implemented using the proposed methods.

Keywords magnetic field sensor, optical fiber sensor, Mach-Zehnder/Sagnac optical fiber interferometer

1 Introduction

Weak magnetic field detection has been paid attention by some researchers [1–4]. The optical fiber interferometers with magnetostrictive material were demonstrated as effective technologies for practical application. As for optical fiber Michelson magnetic field sensor, it eliminated the polarization disturbance of environment by using two Faraday rotation mirrors (FRMs) [5], which enhanced the stability of the sensor remarkably.

Sagnac interferometer has been used for sensing application for its improved sensitivity, which benefits from its optical interferometer path length. However, the optical fiber Sagnac interferometer structure is with disadvantage of the Rayleigh backscatter and polarization wander. Then, the Mach-Zehnder/Sagnac interferometer (MZ-SI) has been proposed for filter [6] and precision sensing [7,8].

In this paper, we applied the MZ-SI for weak magnetic sensing from design and implantation to experiment.

2 Principle description

The principle of the proposed Mach-Zehnder/Sagnac optical fiber interferometer is as follows. The light from the source is split into two routes through a 3-dB coupler and then the two beams transmitted by two fiber arms and couple in the second coupler, which compose a Mach-Zehnder interferometer (MZI). After the second coupler, the light is split into two lights, which transmit in two contrary directions in the Sagnac ring. Since then, two split lights go through two arms of the MZI again. This structure can be regarded as the two cascaded MZI; thus, the two split lights interfere in the fiber triple times.

$$\begin{bmatrix} E_{s1} \\ E_{s2} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \end{bmatrix}, \quad (1)$$

where $\phi = 2\pi n \Delta L / \lambda$, ΔL is the length difference between the two arms in the MZI; E_1 and E_2 are the optical field of input ports; and E_{s1}, E_{s2} are the output in the second coupler.

In the backward transmission, we have the final output in the first coupler:

$$\begin{bmatrix} E_1' \\ E_2' \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & e^{i\phi} \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & i \\ i & 1 \end{bmatrix} \begin{bmatrix} E_{s2} \\ E_{s1} \end{bmatrix}, \quad (2)$$

where E_1' and E_2' are the optical field of final output ports. Considering the input port $E_1 = \sqrt{I}$ (I is the optical intensity of the input port) and $E_2 = 0$, we thus get the intensity expression of the final output:

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$$\begin{cases} I_1 = \dfrac{I}{2}[1 - \cos(2\phi)], \\ I_2 = \dfrac{I}{2}[1 + \cos(2\phi)]. \end{cases} \tag{3}$$

In the part of the MZI, we place the magnetic sensor in one of the two arms, and the other arm is used as the reference arm. When the sensor arm is placed in the magnetic field environment, the magnetostrictive material strain will change the length of the sensing fiber, which induces the phase shift. The two photodetectors (PDs) will detect the phase shift via the output response of the first coupler.

From Ref. [1], we have

$$i_{\text{signal}} = RI_0[1 \pm V\cos(\phi_{\text{b}} + \phi_{\text{e}} + 2\mathrm{d}\phi)], \tag{4}$$

where R is the responsivity of the detectors, I_0 is the average optical power in the final output, V is the visibility of the interferometer, ϕ_{b} is the quadrature control phase bias, ϕ_{e} is the environmental phase drift, and $\mathrm{d}\phi$ is the phase shift induced by the magnetic field.

At the state of quadrature ($\phi_{\text{b}} + \phi_{\text{e}} = \phi_{\text{n}} = \pi/2$), optimum visibility ($V = 1$), and differential amplification output, we have

$$V_{\text{out}} \approx GRI_0(\phi_{\text{n}} + 2\mathrm{d}\phi), \tag{5}$$

where G is the system gain, V_{out} is the voltage of the output, and ϕ_{n} is the phase shift induced by noise.

The optical phase shift $\mathrm{d}\phi$, which is induced by magnetic field, can be expressed as [1,5]

$$\mathrm{d}\phi = \eta\xi e\phi = n\eta\xi kL_{\text{s}}e, \tag{6}$$

where n is the refractive index of fiber, η is the strain-transfer efficiency, ξ is the strain-optic correction factor, k is the optical wave number, L_{s} is the length of sensing arm fiber, and e is the magnetic field-dependent strain. The relationship between the magnetic field and magnetostrictive material strain is

$$e = CH^2, \tag{7}$$

where C is the magnetostrictive coefficient and H is the total external magnetic field.

$$H = H_{\text{d}} + H_{\text{bias}} + h\cos(\omega t), \tag{8}$$

where H_{d} is the direct current (DC) field to be detected, which is a current-controlled Helhots coil; H_{bias} is the bias magnetic field; and $h\cos(\omega t)$ is the dither field.

Therefore, the differential output signal in fiber-optic Mach-Zehnder/Sagnac interferometric magnetic field sensor can be obtained as

$$\begin{aligned} V_{\text{out}} = {} & GRI_0\phi_{\text{n}} + 2GRI_0 n\eta\xi kL_{\text{s}}C\bigg[(H_{\text{d}} + H_{\text{bias}})^2 + \frac{1}{2}h^2 \\ & + 2(H_{\text{d}} + H_{\text{bias}})h\cos(\omega t) + \frac{1}{2}h^2\cos(2\omega t)\bigg]. \end{aligned} \tag{9}$$

Then, we can get the output of the lock-in amplifier:

$$V_{\text{out}} \propto C_{\text{system}}(H_{\text{d}} + H_{\text{bias}})h, \tag{10}$$

where $C_{\text{system}} = 4GRI_0 n\eta\xi kL_{\text{s}}C$ is a constant. To test the DC field under different dither fields, we use the geomagnetic field as the bias field H_{bias}.

3 Experiment technique

The detection part of this paper is the same as that of Ref. [5], which proposed an improved scheme of lock-in amplifier by introducing self phase tracking for weak magnetic field sensor. Because the response output of the structure in this paper is sensitive to polarization, we use polarization controller to maintain the optimum response of the MZ-SI. The experiment setup is shown in Fig. 1.

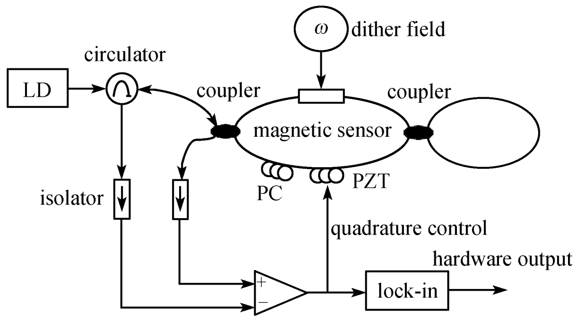

Fig. 1 Experimental setup

The transducer has been wrapped by 6 layers of magnetostrictive material, and the fiber wrapped around the transducer is 30 circles and about 9 m long. The optical part of the interferometer sensor is packed as a stable device and is placed in the total magnetic field in the experiment. Figure 2 shows the stable sensor device.

Fig. 2 Packed device of sensor

We have carried out the experiment on the relationship between measured DC field and the system output response. As can be seen from Fig. 3, the measured DC field maintains linearity with the system output response. From the fitted response of the two sets of results, we can calculate the sensitivities as about 47.8 and 75.6 μV/nT, respectively.

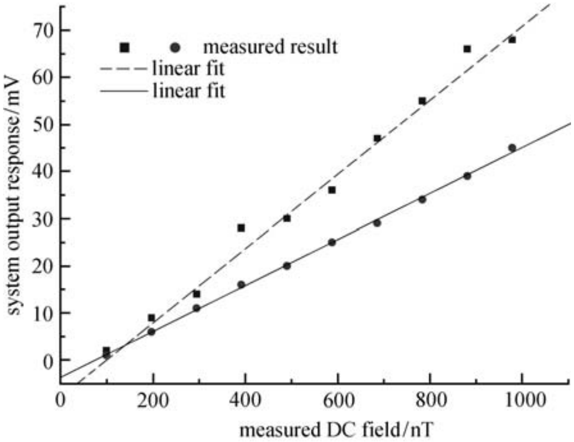

Fig. 3 Output of measured DC field

Compared with experiment results of Ref. [5], the magnetic sensor's sensitivities in this paper are lower. The main reason is that the structure in this paper is sensitive to the polarization of the optical fiber; however, the setup in Ref. [5] is insensitive to the polarization.

4 Conclusion

A new structure for magnetic sensor with Mach-Zehnder/Sagnac hybrid optical fiber interferometer for precision sensing is proposed in this paper. Theoretically, description of the Mach-Zehnder/Sagnac interferometer is given, and some main issues in the magnetic field sensor with optical fiber interferometer are demonstrated with experiments. The results show that the measured DC field maintains linearity with the system output response.

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References

1. Kirkendall C K, Dandridge A. Overview of high performance fibre-optic sensing. Journal of Physics D: Applied Physics, 2004, 37(18): 197–216
2. Dagenais D M, Bucholtz F, Koo K P, Dandridge A. Demonstration of 3 pT/Hz$^{1/2}$ at 10 Hz in a fibre-optic magnetometer. Electronics Letters, 1988, 24(23): 1422–1423
3. Bucholtz F, Dagenais D M, Koo K P. High-frequency fibre-optic magnetometer with 70 fT/Hz$^{1/2}$ resolution. Electronics Letters, 1989, 25(25): 1719–1721
4. Shi C H, Chen J P, Li X W, Ye A L, Zhou J H. Directivity of the magnetostrictive fiber-optic interferometric transducers. IEEE Sensors Journal, 2006, 6(5): 1191–1194
5. Wang X, Chen S, Du Z, Wang X, Shi C, Chen J. Experimental study of some key issues on fiber-optic interferometric sensors detecting weak magnetic field. IEEE Sensors Journal, 2008, 8(7): 1173–1179
6. Huang Y L, Dong X F. Research on dual-pass Mach-Zehnder interferometer filters. Laser Journal, 2006, 27(6): 47–48 (in chinese)
7. Chow J H, Littler I C M, McClelland D E, Gray M B. Backscatter immune Mach-Zehnder-Sagnac hybrid interferometric sensor. Proceedings of SPIE, 2008, 7004: 1–4
8. Chow J H, McClelland D E, Gray M B. Backscatter immune, polarization managed, all fiber Sagnac sensing interferometer. Optics Express, 2007, 15(6): 3310–3319