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An optical fiber magnetic field sensor based on fiber spherical structure interferometer coated by magnetic fluid[*]

XU Feng-tian (徐丰田), LUAN Pan-pan (栾盼盼), JIA Ke-song (贾科松)[**], and ZHANG Ai-ling (张爱玲)
College of Computer & Communication Engineering, Tianjin University of Technology, Tianjin 300384, China

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A novel magnetic field sensor based on optical fiber Mach-Zehnder interferometer (MZI) coated by magnetic fluid (MF) is proposed. The MZI consists of two spherical structures formed on standard single mode fiber (SMF). The interference wavelength and the power of the sensing structure are sensitive to the external refractive index (RI). Since RI of the MF is sensitive to the magnetic field, the magnetic field measurement can be realized by detecting the variation of the interference spectrum. Experimental results show that the wavelength and the power of interference dip both increase with the increase of magnetic field intensity.

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The technique of magnetic field sensor has wide applications in environmental monitoring, aerospace and target recognition[1]. Optical fiber sensors have been extensively investigated due to their advantages of high sensitivity, compact size and low cost[2-5]. However, the optical fiber materials are insensitive to the magnetic field. So the optical fiber magnetic sensors require extra magnetic materials to measure the magnetic field. Magnetic materials have advantages of magneto birefringence, Faraday effect, magnetic variable refractive index (RI), etc. Fiber Bragg grating packed with magneto-strictive material is one of the methods in magnetic field measurement[2-6]. The length of the material changes with magnetic field. As a result, the strain causes a shift of grating resonance wavelength. The etched fiber Bragg grating, combined with magnetic fluid (MF), can also be used to measure magnetic field[7], but the etching process has to employ corrosive chemicals, and it is complex to implement. Long-period grating without etching process combined with magnetic fluid can also be used to measure the strength of magnetic field[8,9]. Besides the grating magnetic sensors, different interferometers are applied to measure magnetic field. An optical fiber sensor with magnetic fluid (MF) inserted in Sagnac interferometer was proposed[10], but the thickness and absorption coefficient of the MF both affect the experiment results. In this paper, we present an optical fiber magnetic field sensor based on fiber double-spherical-structure interferometer. The magnetic field is measured through wavelength dip caused by the interference of the core mode and cladding mode in single mode fiber (SMF).

The structure of the fiber double-spherical-structure interferometric sensor is shown in Fig.1. It contains two spherical structures with a section of SMF in the middle. A fusion splicer is used to fabricate the spherical structures through manual splicing mode. The SMF (8.2 μm /125 μm) without coating is cleaved and set inside the fusion splicer (FITEL S176) with 180 μm beyond the electrode rod. One spherical structure is formed by using discharge intensity of 200 bit and discharge time of 1 300 ms. The discharge intensity and the discharge time of the fusion splicing between spherical structure and SMF are 65 bit and 1 300 ms, respectively. Considering the effect of sensing length on the wavelength interval, the optimal length of the middle SMF is selected as 40 mm.

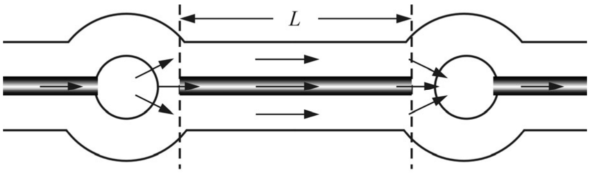

Fig.1 Structure of the fiber double-spherical-structure interferometric sensor

As described, the spherical structures act as mode couplers. The middle SMF acts as the sensing section for parameter detection. The input optical signal is first cou-

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[**] E-mail: yimihua1949@163.com

pled into the core mode and cladding modes of fiber at the first spherical structure. More than one cladding modes are excited. The number of excited cladding modes is determined by the shape and RI distribution of spherical structure. Then the optical signals transmit along the core and cladding in the middle SMF. At the following spherical structure, these cladding modes are coupled into the lead-out SMF, and then they interfere with the fundamental mode under phase matching conditions.

Normally, only one cladding mode is dominant and can interfere with the core mode of SMF. The transmission spectrum is analyzed by using a simple interference model of core mode and guided cladding mode[11,12]. The transmission intensity of the proposed MZI is expressed as

$$I_{\text{out}} = k_1 k_2 I_{\text{in}} + \eta(1-k_1)(1-k_2)I_{\text{in}} + 2I_{\text{in}}\sqrt{\eta k_1 k_2 (1-k_1)(1-k_2)}\cos(\Delta\phi)\,, \tag{1}$$

where k_1 and k_2 are the coupling efficiencies from core mode to core mode at the first and the second spherical-shape structures, respectively, η is the transmission loss of the cladding mode in the middle SMF, I_{in} is the input light intensity, and $\Delta\varphi$ is the phase difference between the core mode and the cladding mode. Supposing the phase shift caused by mode coupling is zero, the phase difference $\Delta\varphi$ is written as

$$\Delta\varphi = \frac{2\pi(n_{\text{core}} - n_{\text{clad}})L}{\lambda}\,, \tag{2}$$

where λ is the wavelength of the propagating light, L is the length of the middle SMF, and $(n_{\text{core}}-n_{\text{clad}})$ is the difference of the effective refractive index between the core and cladding. As the interference signal satisfies its minimum at $\Delta\varphi=(2k+1)\pi$, $(k=0,1,2\cdots)$, the central wavelength of the interference dips can be expressed as

$$\lambda_{\text{dip}} = \frac{2(n_{\text{core}} - n_{\text{clad}})L}{2k+1}\,. \tag{3}$$

When the external RI changes, the effective RI of cladding modes is influenced, but the fundamental mode is not affected. Thus the dip wavelength of the interference spectrum shifts with the change of external RI according to Eq.(3). The wavelength shift with the change of effective RI of cladding mode can be obtained as

$$\Delta\lambda_{\text{dip}} = \lambda_{\text{dip}}\left(\frac{\Delta n_{\text{clad}}}{n_{\text{core}} - n_{\text{clad}}}\right). \tag{4}$$

Besides the mode effective RI, the cladding mode energy leakage will vary with the MF as well. Therefore, the transmission loss of the sensing structure will change with the external magnetic field according to Eq.(1). So the wavelength and transmission loss will change with magnetic field, which can be employed for magnetic field sensing.

In experiment, the optical fiber magnetic field sensor with double spherical structures is fabricated and analyzed. The schematic diagram of the experimental setup is shown in Fig.2. The sensor structure is slowly inserted into a thin tube that is filled with MF. The MF used in the experiment (EMG 605, Ferrotec) is a ferrofluid[8], which is a black-brown translucent liquid. The MF contains magnetic nanoparticles of Fe_3O_4 in water-soluble dispersant, and the nominal diameter of the nanoparticles is 10 nm. The saturation magnetization of the MF is 1.75×10^4 A/m. Light from a broadband light source (BBS) with wavelength range of 1 530–1 560 nm is injected into the input SMF, and the transmission spectrum was recorded by an optical spectrum analyzer (OSA: MS9710B).

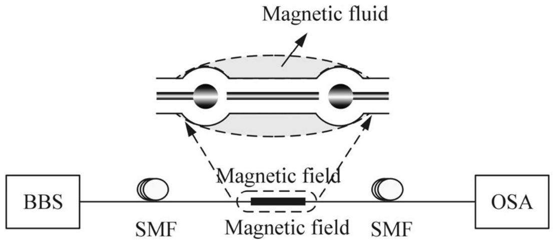

Fig.2 Experimental setup of the double-spherical-structure interferometric magnetic sensor

The sensing structure coated by MF is placed between two poles of a U-type magnet. The strength of the magnetic field is adjusted by changing the distance between the magnet and sensor structure. The external magnetic field strength increases with the decrease of the distance. In experiment, the distance changes from 0 mm to 65 mm with a step of 5 mm. The transmission spectra under some certain distances are shown in Fig.3. The transmission spectra are mainly formed by the interference between the guided cladding mode and core mode, while some other weak excited cladding modes can only influence the main interference pattern slightly. It can be seen from Fig.3 that the transmission spectra have a red shift with the increase of magnetic field strength within a certain range.

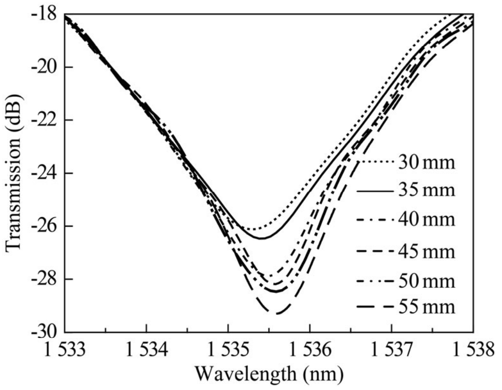

Fig.3 The transmission spectra at different magnetic strengths with different distances between the magnet and sensor structure

Fig.4 shows the wavelength of the selected interference dip versus the distance between magnet and sensor structure. The results show that the wavelength shifting from 1 536.76 nm to 1 535.43 nm presents almost a linear relation with distance in the range from 15 mm to 40 mm. Similarly, in the range from 10 mm to 30 mm, the transmission loss changes from −21.49 dBm to −28.24 dBm, and it has a linear relation with distance as shown in Fig.5. When the U-type magnet is close to the sensor, the wavelength and the transmission loss can be obtained from the linear relation due to the saturation magnetization property of MF. When the U-type magnet is far away from the sensor, the influence on the MF by the external magnetic field strength is too small to change the transmission spectrum.

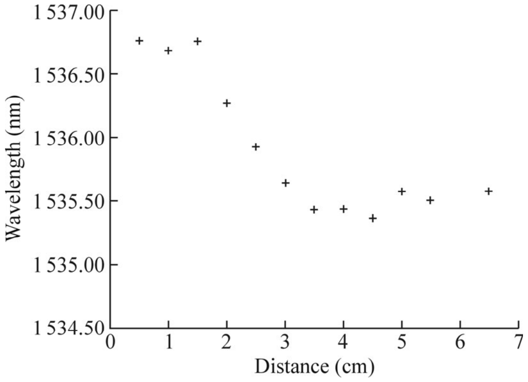

Fig.4 Relationship between distance and the wavelength of the selected interference dip

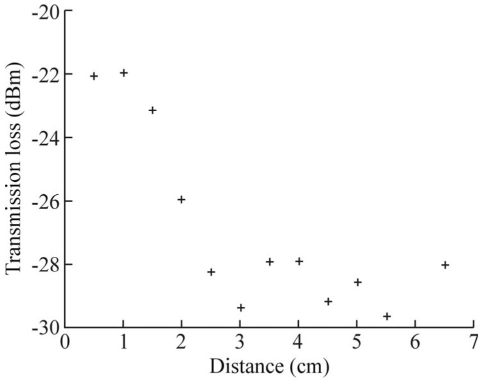

Fig.5 Relationship between the distance and the transmission loss of the selected interference dip

An optical fiber magnetic field sensor with double-spherical-structure interferometer coated by magnetic fluid is proposed and investigated. Through the demonstration of experiment, we find that the double-spherical-structure based magnetic field sensor is sensitive to magnetic field. The magnetic field strength can be measured by monitoring the wavelength shift or the intensity of transmission dip in the interference spectrum. This method is practical in magnetic field measurement, and the sensor with simple structure is easy to fabricate.

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