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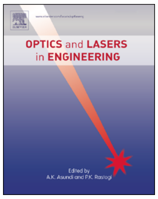

A high-finesse fiber optic Fabry–Perot interferometer based magnetic-field sensor

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ABSTRACT

A high-finesse extrinsic Fabry–Perot interferometric sensor for the measurement of weak dc magnetic fields is demonstrated. The Fabry–Perot cavity is formed by aligning the fiber end-face and the TbDyFe rod end-face, and each end-face is coated by a mirror with a micro-lens. The length of the TbDyFe rod is changed by the variation of an applied dc magnetic field, leading a change of the Fabry–Perot cavity length. By interrogating the white-light interferometric spectrum, the wavelength of the resonant peak is tracked and the length of the Fabry–Perot cavity is obtained. The sensor exhibits a high sensitivity of 1510 nm/mT with a magnetic resolution of 25 nT.

1. Introduction

Magnetic field sensors are widely used in magnetic anomaly detection, magnetic compass, mineral prospecting, non-contact switching, current measurement, etc [1]. Several fiber-optic techniques have been implemented for the measurement of magnetic fields, such as fiber Michelson/Mach–Zehnder interferometric sensors [2,3], birefringence polarimetric fiber-optic sensors [4], fiber Bragg grating sensors [5], and fiber-optic Fabry–Perot sensors [6,7]. Fiber optic extrinsic Fabry–Perot interferometers (EFPI) possess numerous advantages over conventional fiber-optic Michelson and Mach–Zehnder interferometers, including small size, light weight and immune to polarization states [8].

A typical EFPI consists of a Fabry–Perot cavity, which is formed between an input single-mode fiber end-face and a reflecting fiber end-face [7]. Fiber-optic Fabry–Perot interferometric sensors were reported to be highly sensitive to temperature, mechanical vibration, acoustic waves and magnetic fields [6]. In 1997, the fiber optic sensor based on a low-finesse EFPI was demonstrated for the measure of dc magnetic fields with a range of 100–35,000 nT by detecting the variation of output power [9]. In 2004, a compact EFPI-based magnetic field sensor with a resolution of 50 nT is constructed by using a magnetostrictive of gauge at length of 3.2 cm [10]. Both of the EFPI sensors are based on an intensity-type demodulation and low-finesse Fabry–Perot cavity. Though the low-finesse EFPI is easy to fabricate, the detecting sensitivity is limited.

A great interest in fiber optic white-light interferometry (WLI) has grown over past few years mainly due to the ability to determine the absolute optical path difference (OPD) of an interferometer, that is, the ability to measure a static value, such as temperature, strain, dc magnetic field, etc [11]. Meanwhile spectral WLI possesses considerable advantages, including small size, high efficiency, high resolution, etc [11,12].

In this paper, we demonstrate a high-finesse fiber-optic EFPI for the measurement of dc magnetic fields, in which the TbDyFe material is employed as the sensing element. The high-finesse EFPI cavity is constructed by the two end-faces coated with high-reflectivity mirrors, on which there are two micro-lenses. By using the WLI demodulation, the shift of the resonant peak position is easily tracked and the absolute cavity length is also obtained. The sensor exhibits a high sensitivity comparing with the low-finesse EFPI sensing configuration.

2. Operation principle and experiment

The experimental setup based on a high-finesse EFPI for the measurement of weak magnetic fields is shown in Fig. 1. The EFPI sensor is based on an extrinsic Fabry–Perot cavity consisting of one input single-mode fiber end-face and a TbDyFe rod end-face. The single-mode fiber is connected with a cylindrical ceramic core. We fasten the ceramic cores and nonmagnetic tube by using the epoxy resin. Each end-face of the cylindrical ceramic cores is coated by a

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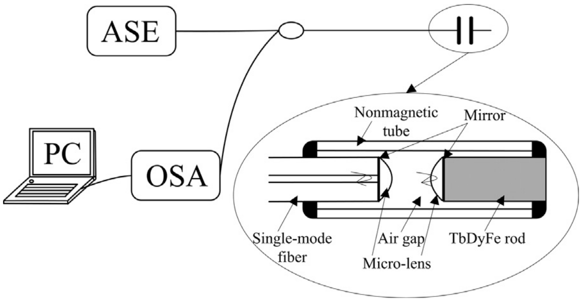

Fig. 1. The experimental setup of the high-finesse EFPI based fiber-optic magnetic-field sensor.

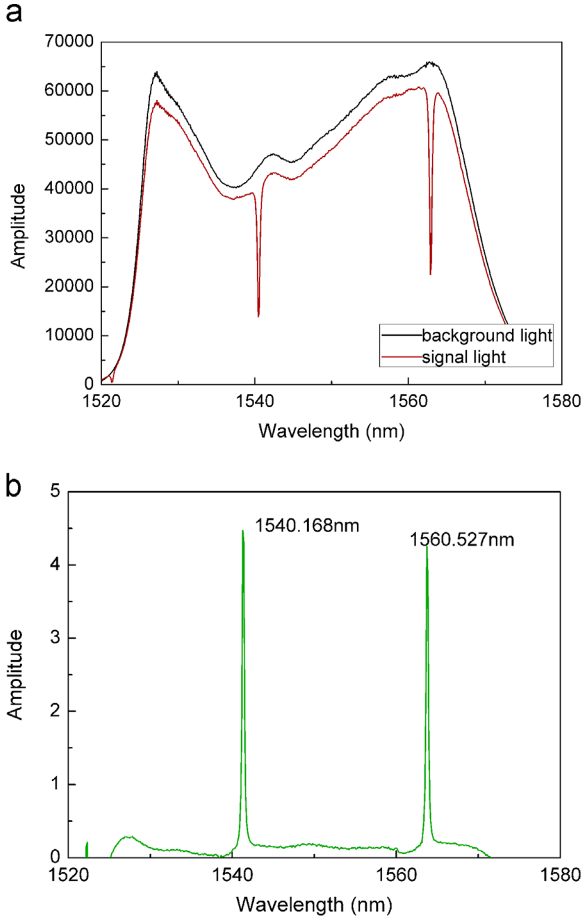

Fig. 2. (a) The reflection spectrum of the high-finesse EFPI. (b) The background spectrum.

high-reflectivity mirror, on which there is a semispherical convex micro-lens, and the detailed manufacturing procedure of the micro-lens is shown in [13]. The two end-faces are aligned by using a ceramic tube, forming an air-gap of a high-finesse EFPI cavity. The TbDyFe material is employed as sensing element and has numerous advantages, such as large magnetostriction, fast response and large coupling coefficient [14]. The TbDyFe rod (REMA-CN, Huizhou South Rare Earth Functional Material Institute Co.) with the size of $\Phi 6.66 \times 16$ mm exhibits a longitudinal strain when it is exposed to magnetic fields parallel to its longitudinal direction. The cavity length changes simultaneously with the change of the rod length. The relationship between the strain of the TbDyFe rod ε and the strength of the applied magnetic field H is given by [15]

$$\varepsilon = \Delta l / l = CH^2 \tag{1}$$

where l is the length of the TbDyFe rod, C is the magnetostricitve material parameter.

The light emitted from the amplified spontaneous emission (ASE) light source with a wavelength covering 1525–1565 nm, is injected into the high-finesse EFPI sensor through a 2×2 coupler. The reflected light signal from the sensor is coupled into a volume phase grating (VPG) based optical spectrum analyzer (OSA, BaySpec FBGA-F-1525-1565). A personal computer is used to process and display the output signal.

The detected light are converted to an electrical signal by the line-array charge-coupled device (CCD) with 512 pixels, and the wavelength resolution is up to 1 pm by using the linear interpolation algorithm. The spectrum of the ASE light source is obtained by using a reflection mirror, then stored in the computer and used to be the background spectrum for the subsequent experiments. The reflection spectrum of the high-finesse EFPI and the background spectrum emitted by the ASE are shown in Fig. 2(a). The outlines of the two spectra are almost the same excluding the two valleys in reflection spectrum. Then, the background spectrum is divided by the reflection spectrum, and a normalized spectrum is obtained, as shown in Fig. 2(b). There are two resonant peaks in the spectrum located at the wavelength of 1540.168 nm and 1560.527 nm. The EFPI has a free spectrum range (FSR) of 20.359 nm, a bandwidth of 0.23 nm, and thus a finesse of 88.

The wavelength shift of the resonant peak is related to the cavity length change, which can be expressed as

$$\Delta d / d = \Delta \lambda / \lambda \tag{2}$$

where λ is the wavelength of the resonant peak, d is the cavity length. The method has a high resolution, but the dymamic range is limited by the FSR in the spectrum.

The cavity length of the EFPI sensor is also measured by tracking the wavelengths of two adjacent resonance peaks (λ_1 and λ_2) that are 2π out of phase, which is expressed as [13]

$$d = 1/2 \ \text{Integer} \left[\lambda_2 / (\lambda_2 - \lambda_1) \right] \lambda_1 \tag{3}$$

This method is used to measure the absolute cavity length of the EFPI sensor with a high resolution, and large dynamic range.

3. Results and discussion

The high-finesse EFPI magnetic-field sensor is experimentally examined in the laboratory environment. The strength of the applied magnetic field is controlled by using a magnet and calibrated with a gaussmeter (WT10E). We change the strength of the applied magnetic field by changing the distance between the magnet and the EFPI sensor. In the experiment, we start to change the strength of applied magnetic field after the sensor remains stable. Applied magnetic field is changed in a range of 0.368–3.086 mT in a short duration of a few seconds that the temperature response has little effect on the sensor. Fig. 3(a) and (b) shows the wavelength of the adjacent two resonant peaks at different magnetic field strength, respectively. The initial resonant peaks are 1538.909 nm and 1560.240 nm respectively, and two peaks shift towards a long wavelength direction with the increase of the magnetic field strength. When the strength of applied magnetic field reaches 1.5 mT, the strain of the TbDyFe rod tends to be saturated and the resonant wavelength has no distinct shift. The cavity length is also calculated according to Eq. (3). The cavity length increases gradually with the increase of dc magnetic field, and reaches saturation at the