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Design of Fiber Magnetic Field Sensor Based on Fiber Bragg Grating Fabry-Perot Cavity Ring-Down Spectroscopy

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Abstract: A novel fiber magnetic sensor based on the fiber Bragg grating Fabry-Perot (FBG-FP) cavity ring-down technique with pulse laser injection is proposed and demonstrated theoretically. A general expression of the intensity of the output electric field is derived, and the effect of the external magnetic field on the ring-down time is discussed. The results show that the output light intensity and the ring-down time of the FBG-FP cavity are in the inverse proportion to the magnitude of the external magnetic field. Our results demonstrate the new concept of the fiber magnetic sensor with the FBG-FP cavity ring-down spectroscopy and the technical feasibility.

Keywords: Fiber magnetic field sensor, fiber Bragg grating, Fabry-Perot cavity, cavity ring-down spectroscopy

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1. Introduction

The fiber magnetic sensor has attracted considerable interest for its advantages of the high sensitivity, simple structure, light weight, easy to make, low cost, long working distance [1–6], etc. Till now, many possibilities have been proposed to generate the fiber magnetic sensor, such as the Mach-Zehnder interferometer in the open-loop mode [7], metallic glass with the detection technique utilizing a square-wave magnetic field modulation [8], and fiber optic Michelson interferometer [9].

Recently, cavity ring-down spectroscopy (CRDS) techniques have been developed rapidly and have great applications in the measurement and sensing of temperature, pressure, gas concentration, etc. The evolution of the cavity ringdown technique has led to a greatly diversified technique (classified by the configurations of ring-down cavities), including the initial mirror-based CRDS [10], fiber end-coated CRDS [11, 12], and very recent fiber Bragg grating (FBG) CRDS [13]. In our previous work, we developed a new method based on the FBG cavity ring-down spectrum to measure the ion doped concentration in solid matters [14].

In this paper, we propose a fiber magnetic field sensor based on the fiber Bragg grating Fabry-Perot (FBG-FP) cavity ring-down spectroscopy, present the operation principle of the proposed sensor, and discuss the effect of the external magnetic field on the ring-down time.

2. Theoretical analysis

The schematic diagram of the proposed fiber magnetic field sensor is shown in Fig. 1. The FBG-FP cavity consists of a couple of identical uniform fiber Bragg gratings (FBG_1 and FBG_2) and a piece of single mode fiber. The magnetostrictive

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material is attached to the surface of the single mode fiber. When an external magnetic field is applied to the section of the fiber with the magnetostrictive material, the induced loss is produced, which leads to an increase in the cavity losses.

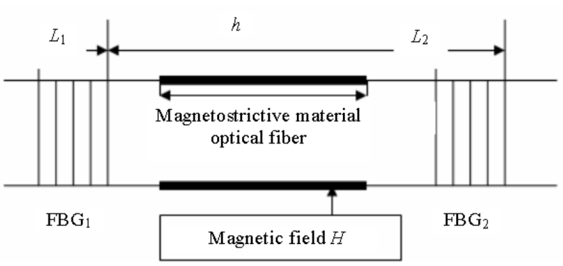

Fig. 1 Schematic diagram of the magnetic field sensor based on the FBG-FP cavity.

Assuming the magnitude of the external magnetic field is H, the longitudinal strain caused by the magnetostrictive material with a length of L can be written as [15]

$$\varepsilon=\frac{\Delta L}{L}=C_{\mathrm{eff}}H \tag{1}$$

where ε is the longitudinal strain, ΔL is the change in the length of the magnetostrictive material, and C_{eff} is the equivalent magnetostrictive coefficient.

The fiber length variation caused by longitudinal magnetostriction is $\Delta L=\varepsilon L$. Meanwhile, birefringence is induced by the magnetostrictive strain forced on the fiber. The variation of the optical fiber refractive index is $\Delta n=-nP\varepsilon$, where P is the elastic coefficient, and n is the refractive index of the single mode fiber.

When the light wave passes through the FBG-FP cavity, the change in the optical path is

$$\Delta\delta=(n+\Delta n)(L+\Delta L)-nL=(1-P-P\varepsilon)n\varepsilon L\,. \tag{2}$$

Because ε is small and the item of ε^2 can be ignored, we obtain

$$\Delta\delta\approx(1-P)n\varepsilon L\,. \tag{3}$$

On the other hand, $\Delta\delta=n\Delta h$, and we have

$$\Delta h=\frac{\Delta\delta}{n}=(1-P)C_{\mathrm{eff}}LH=MH \tag{4}$$

where $M=(1-P)C_{\mathrm{eff}}L$. When the magnetostrictive material is fixed, M is a constant. Whereby, the fiber phase variation caused by the external magnetic field can be written as

$$\Delta\Phi=2\beta\Delta h=2\beta MH \tag{5}$$

where β is the propagation constant.

The power transmission of the FBG-FP cavity is [16]

$$T=\frac{(1-R_g)^2}{(1-R_g)^2+4R_g\sin^2(\beta h-\Phi_r)} \tag{6}$$

where R_g is the reflectivity of the FBG, and Φ_r is fiber Bragg grating phase factor. $\beta h=\frac{\Phi}{2}$, and $\Phi=\Phi_0+\Delta\Phi$, where Φ_0 is the phase of the single mode fiber without the external magnetic field.

By continuously injecting monochromatic light with the amplitude of E_0 and intensity of I_0 ($I_0\propto E_0^2$) into the cavity, the complex cavity field amplitude after p (or t=2hnp/c) accumulated roundtrips will be [12]

$$E_1=\frac{1-r^{p+1}\exp[-\mathrm{i}\Phi(p+1)]}{1-r\exp(-\mathrm{i}\Phi)}E_0 \tag{7}$$

where $\mathrm{i}=\sqrt{-1}$, and r is the attenuation factor of the FBG-FP cavity.

When the injecting phase of the light is stopped, the remaining light in the cavity still circulates within the resonator for q (or $t=2hnq/c$) additional roundtrips, and the total electric field after the FBG-FP cavity can be written as

$$E_2=r^q\exp(-\mathrm{i}n\Phi)E_1\,. \tag{8}$$

Substituting (7) into (8), we have

$$E_2=r^q\,\frac{1-r^{p+1}\exp[-\mathrm{i}\Phi(p+1)]}{1-r\exp(-\mathrm{i}\Phi)}\exp(-\mathrm{i}q\Phi)E_0\,. \tag{9}$$

The intensity of the output electric field is

$$I=E_2E_2^* \tag{10}$$

where E_2^* is the conjugate of E_2. The ratio of the output intensity to the input intensity is

$$R=\frac{I}{I_0}\,. \tag{11}$$

3. Results and discussions

It is assumed that the attenuation factor of the FBG-FP cavity is r = 0.98, the refractive index of the single mode fiber is 1.5, and the cavity length is 0.5 m. The effect of the external magnetic field on the FBG-FP cavity output characteristics is shown in Fig. 2. It demonstrates three phases: build-up, stability, and ring-down phases. The build-up phase shows the injection of the light, the stability phase expresses that the cavity reaches a maximum, and the ring-down phase denotes that the injection of the light is ceased. Setting the external magnetic fields as 0 kA/m and 15 kA/m, respectively, the input light intensity I_0 of different external magnetic fields is the same. It is shown that the output light intensity of the FBG-FP cavity and ring-down time are in the inverse proportion to the magnitude of the external magnetic field, because the cavity loss is in the proportion to the magnitude of the external magnetic field.

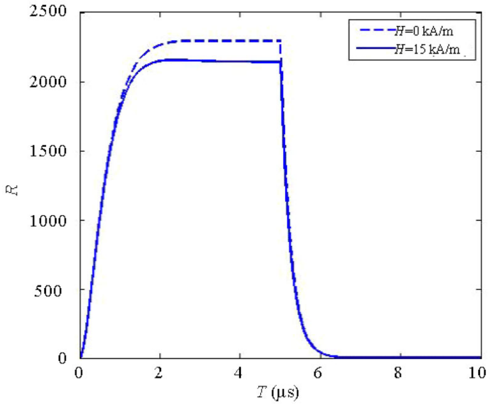

Fig. 2 Output performance of the FBG-FP cavity with the magnetostrictive sensor cell.

Figure 3 shows the relationship between the ring-down time and the external magnetic field. It is demonstrated that the ring-down time is in the nearly inverse proportion to the magnitude of the external magnetic field. When the magnitude of the external magnetic field increases from 0 kA/m to 23 kA/m, the FBG FP-cavity ring-down time decreases from 1081 ns to 1067 ns.

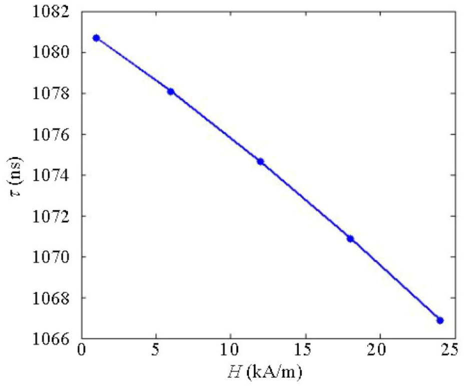

Fig. 3 Relationship between the ring-down time and external magnetic field.

4. Conclusions

In this paper, we propose a fiber magnetic field sensor based on the FBG-FP cavity ring-down spectroscopy and present the operation principle of the proposed sensor. When the magnitude of the external magnetic field increases from 0 kA/m to 23 kA/m, the FBG-FP cavity ring-down time decreases from 1081 ns to 1067 ns.

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