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Quasi-Distributed Magnetic Field Fiber Sensors Integrated with Magnetostrictive Rod in OFDR System

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Abstract: We have proposed and designed a fiber-optic magnetic field sensors based on magnetostriction, of which the magnetostrictive induced strain of magnetostrictive rod attached to an optical fiber can be measured by optical frequency-domain reflectometry (OFDR). By analyzing the stress transfer process at the interface between the magnetostrictive rod and the sensing optical fiber, we find that the sensor sensitivity is mainly related to the magnetostrictive material and bond width. The experimental results show the sensor performance under different magnetostrictive rods and radiuses. The sensitivity of the Fe-Ga-based sensor is up to $5.05 \mu\epsilon/\text{mT}$, while the sensitivity of the Tb-Dy-Fe-based sensor is up to $3.42 \mu\epsilon/\text{mT}$. The proposed sensor can easily construct a sensor network for quasi-distributed fiber-optic magnetic field sensing, which can be used to monitor magnetic fields at more than one point.

Keywords: magnetic field sensor; fiber-optic sensors; magnetostriction; optical frequency-domain reflectometry



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1. Introduction

Magnetic field sensors play an important role in many applications, including electric current measurement, magnetic compass, traffic control, astronomy, and geological and medical applications [1]. Most conventional magnetic field sensors are based on metal structures, such as search coil magnetometers, which can measure magnetic fields by detecting the current changes in the coils. It generally has the disadvantages of complex insulation structures (typically using oil or solid insulation), high cost, and difficulty in digitization when used in power applications [2,3]. Thankfully, fiber-optic magnetic field sensors are an effective way to overcome these shortcomings due to the immunity to electromagnetic interference, and with the merits of a compact size, high sensitivity.

Fiber-optic magnetic field sensors can be mainly classified into two categories according to the sensing principles. One is based on the Faraday magneto-optical effect and the other is based on the magnetostrictive effect. The Faraday magneto-optical effect was first discovered by M. Faraday in 1845 [4]. It is found that the rotation of the polarization plane of linearly polarized light propagates through a piece of borosilicate lead glass placed in a magnetic field [5].

For the method of the magnetostrictive material, a magnetostrictive material is attached to an optical fiber, and the induced strain can transfer onto the fiber and is demodulated by fiber sensing schemes such as interferometers and fiber Bragg grating (FBG) [6,7]. In 2005, Li et al. achieved the quasi-distributed measurement of the magnetic field by measuring the shift of the FBG wavelength caused by magnetostriction, and the sensitivity obtained was 1.8 nm/Oe [8]. In addition to FBG-based methods, Masoudi et al. first

reported a distributed sensor using a phase-sensitive optical time-domain reflectometry to detect magnetic fields by measuring the strain induced by magnetostriction on the optical fiber [9]. Furthermore, quasi-distributed fiber-optic magnetic field systems have recently received attention, and Cheng et al. proposed a quasi-distributed fiber magnetic field sensing system based on the frequency-shifted interferometry fiber cavity ringdown (FSI-FCRD) technique, where multiple sensing units are connected in series in a frequency-shifted interferometer [10]. The highest sensitivity was 7.5×10^{-4} dB/Oe. Compared to these techniques, the optical frequency-domain reflectometry (OFDR) has the advantages of a high sensitivity and high spatial resolution, which can be used for quasi-distributed fiber-optic magnetic field measurements. In 2015, Du et al. first reported an OFDR-based optical distributed magnetic field sensing system where the sensing fiber was attached in two thin plates of a magnetostrictive Fe-Co-V alloy, where the magnetic field-induced strain can shift the frequency of the reflected signal [11]. Du et al. subsequently also showed that it can be used as a current sensor, capable of measuring current ranges from 0~11.80 A and 0~12.14 A, with a minimum measurable current variation of 0.30 A [12]. Although some preliminary works of magnetostrictive measurements by OFDR have been done, comprehensive study on various magnetostrictive materials is still lacking and is of great interest.

In this paper, an optical fiber magnetic field sensor integrated with magnetostrictive rod by OFDR is proposed and demonstrated. In our scheme, a standard single-mode fiber (SMF) was bonded on a magnetostrictive rod by epoxy glue. The strain applied to the SMF caused by the external magnetic field (B) was detected by OFDR. To investigate the enhanced sensor sensitivity, the mechanics of bonding and shear transfer in magnetostrictive rod and optical fiber sensors were analyzed. The analysis showed that the sensitivity of the fiber optic sensor depends mainly on the bonding width between the magnetostrictive rod and the fiber. The effect of different magnetostrictive rods (Fe-Ga, Tb-Dy-Fe, and Ni) and radius (1.2 mm and 0.4 mm) on the sensitivity is experimentally demonstrated. The experimental results show that Tb-Dy-Fe has good magnetostriction in the magnetic field strength range of 0–185 mT, with a sensitivity of up to $3.42 \mu\epsilon/\text{mT}$. Fe-Ga has the advantage of a larger magnetostriction coefficient within small magnetic field strength of 0–20 mT, with a sensitivity up to $5.05 \mu\epsilon/\text{mT}$, as well as easier to sensor networks by using the whole optical fiber of OFDR for quasi-distributed fiber-optic magnetic field sensing.

2. Operation Principle of the Sensor

When the optical fiber integrated with magnetostrictive material is used as a sensor for magnetic field, the sensitivity depends on the bonding conditions between the optical fiber and the magnetostrictive material. Figure 1a shows the schematic diagram of the 3D four-layer model structure. Figure 1b shows free-body diagrams of the sensor configuration stress distribution. It can be seen that the fiber is strained due to the stress transfer from the magnetostrictive rod through the mid-layer when the magnetostrictive rod was subjected to strain due to magnetostriction under external magnetic field.

As shown in Figure 1b, the strain on the magnetostrictive rod is transferred to the fibers through the adhesive layer (τ_{ma}), the protective layer (τ_{ap}), and the fiber (τ_{pf}) by shear force, which causes strain on the fibers. The relationship between the strain in the fiber (ϵ_f) and the strain in the magnetostrictive rod (ϵ_m) can be obtained by the following basic assumptions, that the protective coating is an ideal elastic plastic material, and a perfect bonding exists at each interface. The stress balance of the fiber, protective coating, adhesive layer, and magnetostrictive rod, and the displacement relationship can be obtained from the strain transferred to the fiber by magnetostriction, as follows [13]:

$$\epsilon_f = \left(1 - \frac{\sinh(kL)}{kL \cosh(kL)}\right) \epsilon_m = \alpha \epsilon_m, \quad (1)$$

where k is

$$k = \frac{1}{\sqrt{\frac{1}{d} \frac{(r_a - r_p)(E_p A_p + E_f A_f + E_a A_a)}{G_a} + \frac{(r_p - r_f)(E_p A_p + E_f A_f)}{2\pi r_p G_p}}} \quad (2)$$

where L represents the sensing gauge length, α represents the strain of the fiber transfer efficiency, and ε_f , ε_m are the normal strain of the fiber and magnetostrictive rod. r_f , r_p , r_m represent the radius of the fiber, protective coating, and magnetostrictive rod, respectively, A_f , A_p is the circular cross-sectional area of the fiber and protective coating, A_a is the cross-sectional area of the adhesive layer, and h , d represent adhesive layer bond height and width.

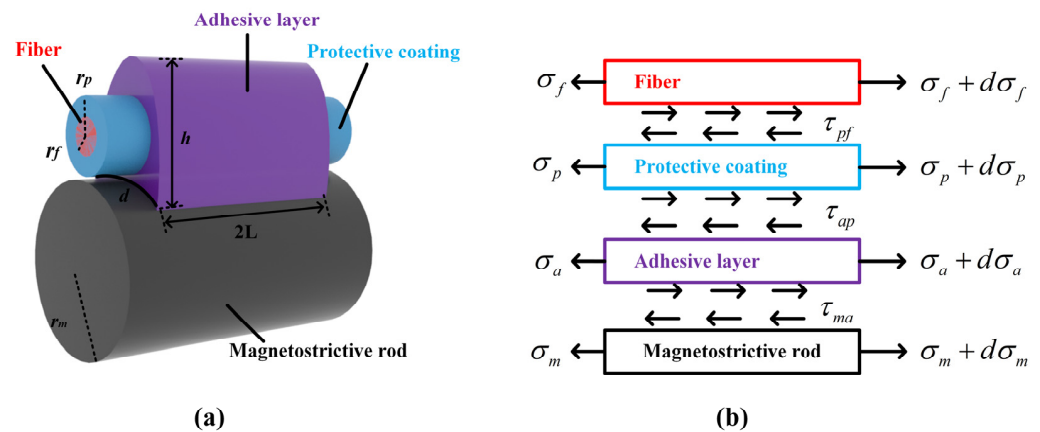


Figure 1. (a) Schematic diagram of the 3D four-layer model structure; (b) free-body diagrams of the sensor configuration stress distribution.

OFDR uses a frequency swept laser beam that is coupled to an optical interferometer. The output of the frequency swept laser is split between the reference and measurement arms of an interferometer. In the measurement path, the light is further split to interrogate a length of the fiber under test (FUT) and to return the scattered light. As the laser is linearly swept in the optical frequency, the interference between the measurement and reference field is recorded using optical detectors [14]. Rayleigh backscattering is caused by random refractive index fluctuations along an optical fiber. The strain change will cause a local Rayleigh backscattering spectra (RBS) shift. Without considering the effect of temperature, the strain ε_f versus the measured shift ($\Delta\lambda$) of the RBS can be given by [15]:

$$\varepsilon_f = \frac{\Delta\lambda}{\lambda K_\varepsilon} = \alpha \varepsilon_m \quad (3)$$

where λ is the mean optical wavelength, $\Delta\lambda$ is the shift of the optical wavelength, and K_ε is the strain calibration constant.

Equation (1) shows that the magnetostrictive strain is transferred to the fiber by shear through the mid-layer, and strain transfer efficiency is positively correlated with fiber length (L) and adhesive bond width d , and negatively correlated with adhesive bond height (h), and the transfer efficiency is a maximum at the sensor center (at $x = 0$) [13]. Especially for the bond width d , which represents the bonding area between the adhesive layer and the magnetostrictive rod. It is difficult to obtain a large bonding width d when the magnetostrictive rod diameter is small, and the strain transfer efficiency will be low at that time.

In our experiments, when the applied magnetic field increased, the strain of magnetostrictive rod increased because of the magnetostriction. As a result, the effective strain on optical fiber increased due to the strain transfer from magnetostriction based on Equation (1). According to Equation (3), the measured shift of the scattering spectrum with the strain of

fiber changed. Such a magnetostriction-based structure can be used to sense the applied magnetic field by OFDR.

3. Experiments and Results

3.1. Fabrication of the Sensors

First, a piece of SMF was placed along the magnetostrictive rod and was bonded to it. The magnetostrictive rod with a length of 5 cm was used. The epoxy glue was used to bond SMF to the surface of the magnetostrictive rod, and we waited for a 24-h curing time to enhance the bonding. Finally, the SMF integrated with magnetostrictive rod structure was built.

In order to characterize the magnetic field sensing performance of different types of magnetostrictive materials, Tb-Dy-Fe, Fe-Ga, and Ni were used in this work, which were provided by Suzhou Avon Alloys, China. Their magnetostriction coefficients are 900 ppm, 170 ppm and -30 ppm, respectively. In addition, the effect of the magnetostrictive rod's diameter was also characterized. The samples' cases are shown in Table 1.

Table 1. Parameters of the sample.

Case	Materials	r_m (mm)	Fiber
#1	Fe-Ga	1.2	SMF
#2	Tb-Dy-Fe	1.2	SMF
#3	Ni	1.2	SMF
#4	Fe-Ga	0.4	SMF
#5	Fe-Ga	0.4	Bare SMF

3.2. Experimental Setup

Our experimental setup for the magnetic field measurement is shown in Figure 2. The strength of the magnetic field generated by the electromagnet is controlled by the electric current. OFDR (OBR 4600) was utilized to perform strain sensing based on magnetostriction. We accessed the sensor into the OFDR and put it on a platform in the center of the two electromagnets which were spaced 8 cm apart, as shown in Figure 2. A Tesla meter was placed in the air gap of the two electromagnets, and a series of magnetic field strength could be obtained by changing the input current of the electromagnet. The experiments were performed at room temperature. It should be noted that an unstable environment, such as vibration and temperature variation, could lead to a measurement error. Due to the photoelastic effect, vibrations in the environment can affect the refractive index of the fiber, thus shifting RBS in OFDR, and cause measurement error; similarly, temperature changes also affect the refractive index of the fiber, and thus cause measurement errors. In extreme environments, cross-sensitivities occur from multiple parameters, which can be corrected by compensation methods [16,17].

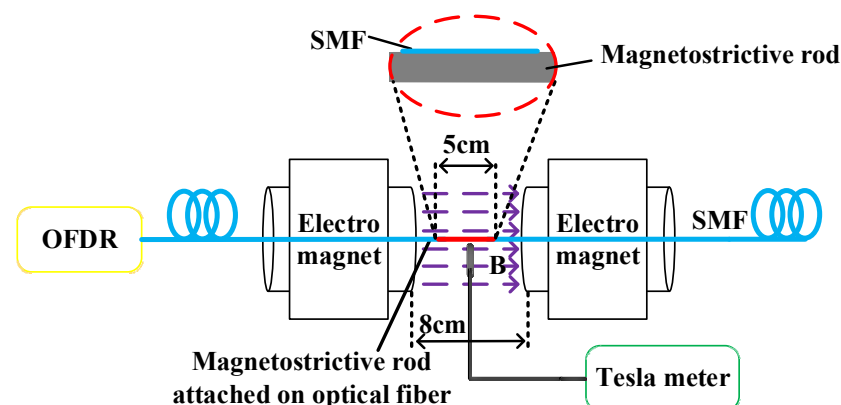


Figure 2. Schematic diagram of the experimental setup.

3.3. Results and Discussion

The samples of sensors #1–5 introduced in Table 1 were placed in the experimental setup, as shown in Figure 2. In the experiment, the sensors were tested by the OFDR three times, and the strain versus magnetic field strength were plotted with the error bar calculated from the data of the three times. The strain response obtained by the OFDR are shown in Figure 3. For #1-Fe-Ga, the slope is high in the range of 0–15 mT and the strain versus the magnetic field strength is almost linear. However, as the magnetic field strength larger than 20 mT, the magnetostriction reaches saturation, the strain in the fiber maintained at about 78 $\mu\epsilon$. For #2-Tb-Dy-Fe, the slope is high in the range of 0–40 mT, and the relationship between the strain and magnetic field strength is almost linear, which is optimal as the slope decreases slowly in the range of 40–185 mT, and the strain is finally 245.50 $\mu\epsilon$ at 185 mT. For #3-Ni, which is different from #1-Fe-Ga and #2-Tb-Dy-Fe, the negative strain generated under the applied magnetic field is smaller ($-7.25 \mu\epsilon$ at 52.1 mT). Because #1-Fe-Ga, #4-Fe-Ga-SMF, and #5-Fe-Ga-Bare-SMF are all based on Fe-Ga, the samples of #4 and #5 have the same trend as #1. All of the above results show that the different magnetostrictive materials have different response behaviors to the applied magnetic field strength. In the initial stage, the magnetostrictive effect can be seen as a linear response to the magnetic field strength. However, as the magnetic field strength increases, the magnetic domain appears to be saturated, which leads to the nonlinear response, as shown in Figure 3. Additionally, the non-uniform glue layer could lead to an error, which could be optimized later. The main reason for the nonlinearity could be the magnetic field saturation phenomenon of magnetostrictive materials [18]. The reason for the change in the length of magnetostrictive materials is the result of the rotation of small magnetic domains, and this rotation and reorientation leads to internal strain in the structure of the material. The strain in the structure leads to a stretching of the material in the direction of the magnetic field, and the degree of the re-orientation magnetic domains depends on the magnetic field strength. When all the magnetic domains have become aligned with the magnetic field, the saturation point has been achieved, and no further magnetostriction can be produced by increasing the applied magnetic field [19].

The sensor repeatability can be seen in Figure 3. These sensors have better repeatability, and the strain errors are all less than 3 $\mu\epsilon$. The experimental error may be caused by temperature or vibration. For the issue of hysteresis of the sensor, which is determined by the magnetostrictive rod and the adhesive layer, there is no significant strain hysteresis problem under the DC magnetic field in this experiment. If it is under the high frequency AC magnetic field, the sensor may have a strain hysteresis problem due to the hysteresis of strain transfer from the adhesive layer. The sensitivity of the magnetic sensor is defined as $d\epsilon_f/dB$, where ϵ_f represents the strain of sensor and B represents the applied magnetic field strength. The sensor sensitivities of #1–5 are shown in Table 2. #1-Fe-Ga has the highest sensitivity of approximate 5.05 $\mu\epsilon/\text{mT}$ compared to other sensors. #2-Tb-Dy-Fe has a sensitivity of approximate 3.42 $\mu\epsilon/\text{mT}$. It manifests a nonlinear response with the test range of 185 mT where a large strain of 245.50 $\mu\epsilon$ is achieved. The sensitivity of the #3-Ni is quite lower than that of #1 and #2, and manifests a negative strain response.

Table 2. Sensitivity of the sample.

Case	Materials	Sensitivity ($\mu\epsilon/\text{mT}$)	R ² (Linear of Fit)
#1	Fe-Ga	5.05	0.996
#2	Tb-Dy-Fe	3.42	0.999
#3	Ni	−0.14	0.833
#4	Fe-Ga	0.89	0.939
#5	Fe-Ga	1.27	0.988

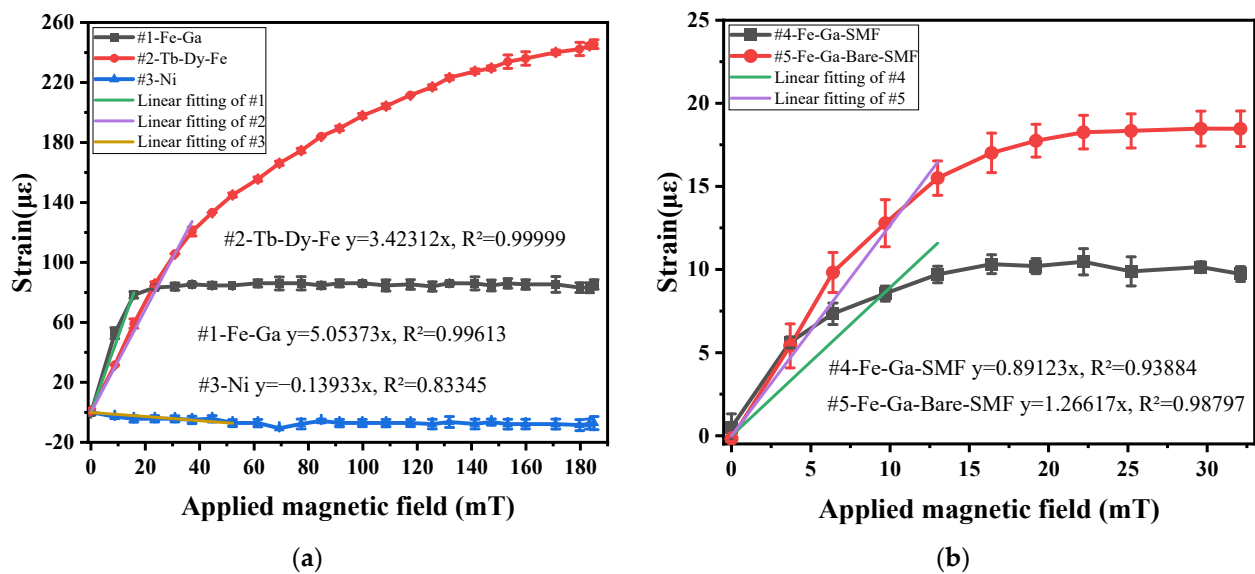


Figure 3. The comparison between samples as shown in Table 1: (a) the sensors of #1–3; (b) the sensors of #4 and #5.

For #4-Fe-Ga-SMF and #5-Fe-Ga-Bare-SMF, the sensitivity is much lower compared to #1, which is because the radius of 0.4 mm of the magnetostrictive rod is smaller than that of #1. The larger magnetostrictive rod will achieve a larger bond width d . According to Equation (1), a larger bonding width has a greater large magnetostrictive strain transfer efficiency. The sensitivity of #5-Fe-Ga-Bare-SMF is higher than that of #4-Fe-Ga-SMF, because the optical fiber coating can reduce the strain transfer. Here only Fe-Ga was chosen as a typical sample for investigating the effect of the optical fiber coating on the sensitivity, while for other magnetostrictive materials, similar results should be achieved from the principle. As a result, different magnetostrictive materials have variable strain characteristics, and each material has different strains and linear working ranges. It is necessary to select a specific magnetostrictive material according to the needs of the application for the working range, or to make some additional arrangements for the performance of the magnetic field sensor to be optimized—for example, a typical optimal arrangement is to use a permanent magnet to generate a magnetic field with a bias, keeping the sensor in an optimal linear operating region.

The effect of direction of the applied magnetic field was also investigated. The results for #1 are shown in Figure 4. The sensor orientation is horizontal to the magnetic field direction denoted as 0° , and the strain response decreases by 18.9% (at 9.7 mT) when the sensor is rotated 45° with respect to the magnetic field direction, while the magnetostrictive effect largely disappears at 90° . This is caused by the fabrication process of the magnetostrictive rod, where the directional solidification technology is generally used. The magnetostrictive material is specifically controlled by using axially oriented solidification to encourage a crystallographically aligned structure. As a result, the magnetostrictive rod of the magnetostriction is enhanced in the axial magnetic field direction and reduced in the other magnetic field directions [20].

To investigate the magnetic field sensor network based on the OFDR system, two sensors are integrated into the sensing fiber. The strain response traces of the two sensors in the magnetic field at the same time are shown in Figure 5. It shows #1-Fe-Ga at 2.65 m to 2.70 m and #2-Tb-Dy-Fe at 3.22 m to 3.28 m, where the spatial resolution of 1 cm is set. The magnetic field strength varies from 0 mT to 185 mT with an increment of about 8 mT, and the strain increases with the increase of the magnetic field strength. In addition, the strain located at the center of the sensing fiber (#1 at 2.67 m, #2 at 3.25 m, #4 at 2.32 m, and #5 at 1.97 m) is the greatest. This is because the strain transmission efficiency is the greatest in the center of the sensor according to Equation (1). Similarly, the strain response traces of

the #4-Fe-Ga-SMF and #5-Fe-Ga-Bare-SMF are shown in Figure 5b, with #4-Fe-Ga-SMF at 2.28 m to 2.36 m and #5-Fe-Ga-Bare-SMF at 1.93 m to 2.01 m. The magnetic field strength is varied from 0 mT to 32 mT with an increment of about 3.2 mT, and the strain increases with the increase in the magnetic field. In addition, the location of each fiber sensor in the sensor network is preset, and by relying on the OFDR distributed strain sensing, the location corresponding to the strain of the fiber sensor under the magnetic field can be obtained, so that a quasi-distributed sensor can be realized. The quasi-distributed magnetic field sensing scheme is implemented by our proposed sensors as follows. Firstly, the sensing length needs to be considered, where OFDR is excellent for short sensing lengths (<70 m), while longer measurement distances (2 km) are possible at the cost of both spatial resolution and strain resolution. The spatial resolution of the OFDR system limits the minimum spacing of the sensors, which determines the number of sensors that can be connected. As a typical example, in a sensing length of 70 m, every 3 m fiber is connected sequentially and a sensing network comprising approximate 20 points can be constructed. Finally, the strain of each sensor is detected by the OFDR system and the distance is used to locate the sensor point. In practical applications, the spatial resolution of the OFDR system limits the minimum spacing of the sensors and the signal-to-noise ratio limits the sensing distance, so the deployment needs to consider both the laser and noise, etc.

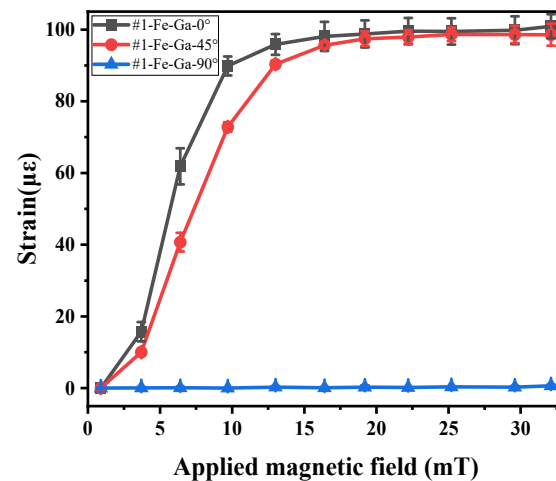


Figure 4. The #1-Fe-Ga sensor response changes with the angle between the sensor axis and the applied magnetic field.

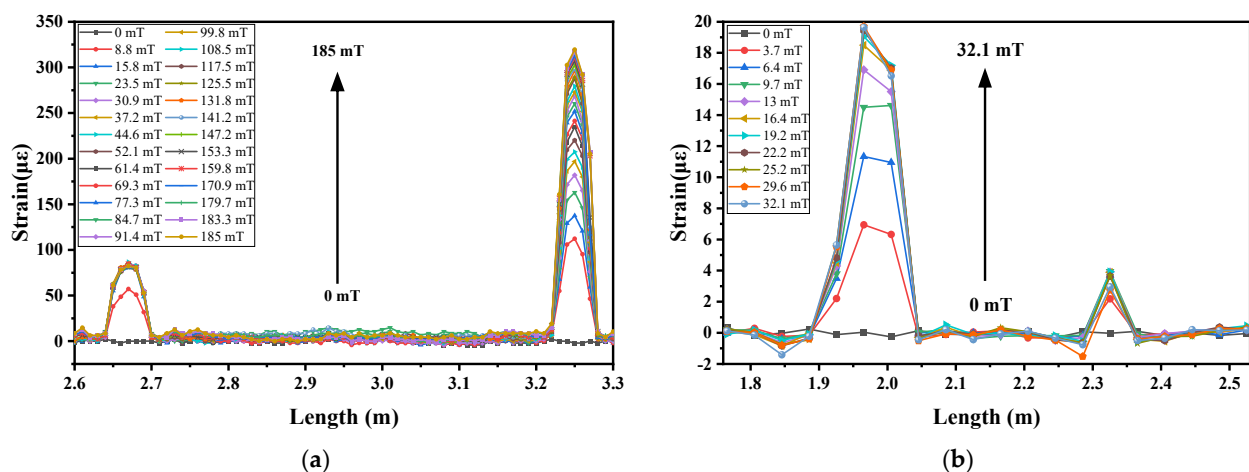


Figure 5. Strain response traces induced by magnetic field for (a) the sensor of #1-Fe-Ga and #2-Tb-Dy-Fe at 2.67 m and 3.25 m, respectively; (b) the sensor of #4-Fe-Ga-SMF and #5-Fe-Ga-Bare-SMF at 2.32 m and 1.97 m, respectively.

4. Conclusions

In this work, a fiber-optic magnetic field sensor integrated with magnetostrictive rod has been demonstrated experimentally. By analyzing the shear force transfer mechanism in the magnetostrictive rod and the optical fiber sensor, it is found that the strain transfer is mainly related to the magnetostrictive material and the bonding width. We experimentally verified the performance of different magnetostrictive materials, and the bonding width d that can be increased to improve the sensitivity, which can be selected according to the application, and suitable magnetostrictive materials can be chosen according to different sensitivities and dynamic ranges. In addition, traditional magnetic field sensors are point magnetic field sensors, while our proposed sensor can set-up a sensor network for quasi-distributed fiber optic magnetic field sensing, and our sensor is based on communication fiber, so it is compatible with current fiber optic communication systems and have a high magnetic sensing sensitivity. Therefore, this new type of optic fiber magnetic field sensor has potential application prospects in magnetic field sensor network systems.

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Conflicts of Interest: The authors declare no conflict of interest.

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