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Magnetostrictive composite–fiber Bragg grating (MC–FBG) magnetic field sensor

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ABSTRACT

We report a magnetostrictive composite–fiber Bragg grating (MC–FBG) magnetic field sensor based on the direct coupling of the magnetostrictive strain in an epoxy-bonded Terfenol-D particle pseudo-1–3 MC actuator with a FBG strain sensor. The MC–FBG sensor exhibits a large and fairly linear quasistatic peak wavelength shift of 0.68 nm under an applied magnetic field of 146 kA/m and a wide extrinsic magneto-optical signal frequency range up to at least 60 kHz. These quasistatic and dynamic characteristics, together with the electromagnetic interference immunity, large-scale multiplexing potential and self-reference capability, enable the application of the MC–FBG sensor in distributed magnetic field sensing over long distances.

1. Introduction

Fiber Bragg grating (FBG) sensors have become an important class of sensing device for long-distance and distributed sensing of various types of physical parameters such as strain, pressure, temperature, etc. in a broad domain of industrial fields [1,2]. However, FBG sensors fall short of any magnetic field sensing because of their inherently weak magneto-optical Faraday effect [3]. Recently, it has been demonstrated that a FBG can be bonded onto a monolithic Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_{1.92}$) magnetostrictive alloy to form a magnetostrictive alloy–FBG (MA–FBG) sensor for magnetic field or electric current sensing [4–8]. In the reported sensor design, the MA functions as a magnetic actuator with magnetostrictive strain as the output, while the FBG operates as a strain sensor with the magnetostrictive strain from the MA as the input. Compared to conventional non-optical magnetic field or electric current sensors such as Hall-effect sensors and reluctance coils [9], this type of MA–FBG sensor features a high level of immunity to electromagnetic interference, a great potential for large-scale multiplexing and a large capability for self-reference [4–8]. Unfortunately, since the monolithic Terfenol-D MA used in the reported sensor design is an excellent conductor with an extremely low electrical resistivity of about 0.6 μΩ cm, operation of monolithic Terfenol-D MA and its associated devices above a few kilohertz is significantly limited by the presence of eddy-current losses [10,11]. Another crucial problems associated with monolithic Terfenol-D MA are high mechanical brittleness, heavy weight (density as high as 9250 kg/m^3), limited shape variety and high material cost [11].

In this paper, we present results on the fabrication and evaluation of a magnetostrictive composite–FBG (MC–FBG) magnetic field sensor developed using an epoxy-bonded Terfenol-D particle pseudo-1–3 MC as a magnetic actuator and a FBG as a strain sensor. This MC-based FBG sensor not only possesses a large quasistatic peak wavelength shift of 0.68 nm at an applied magnetic field of 146 kA/m and a wide extrinsic magneto-optical signal frequency range in excess of 60 kHz, but also alleviates the brittleness, weight, shape and cost problems intrinsic in state-of-the-art MA-based FBG sensors.

2. Sensor structure and fabrication

Fig. 1 shows the schematic diagram of the proposed MC–FBG magnetic field sensor formed by bonding a FBG onto a bar-shaped MC. The MC bar was fabricated in-house using Terfenol-D magnetostrictive particles with randomly distributed sizes of 10–300 μm in at least one dimension (Gansu Tianxing Rare Earth Functional Materials Co., Ltd., China) as the active phase and Spurr epoxy with a dynamic viscosity of 60 mPa s at room temperature (Polysciences, Inc., PA) as the passive phase. Predetermined quantities of Terfenol-D particles and Spurr epoxy were homogenously mixed in a bronze mold with a rectangular cavity of length 30 mm, width 12 mm and height 12 mm. The mixed slurry was degassed under vacuum for 30 min to eliminate air bubbles. The mold was sealed and placed between a pair of Nd–Fe–B permanent magnets to experience a uniform magnetic field of about 150 kA/m along the length direction. This caused the embedded Terfenol-D particles to

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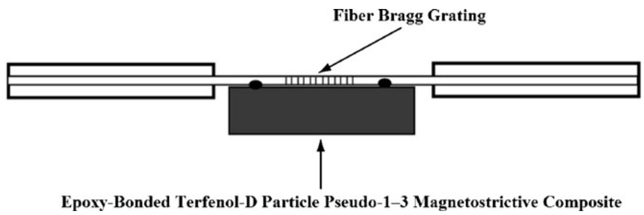

Fig. 1. Schematic diagram of the proposed MC–FBG magnetic field sensor.

lengthwise-align with the magnetic flux lines in the Spurr epoxy matrix and thereby produced particulate chains similar to aligned pseudo-fiber composites or, in general, a pseudo-1–3 MC [12,13]. The entire mold-magnet assembly was placed in a temperature-controlled chamber at 70 °C for 8 h to ensure a proper cure of the Spurr epoxy for achieving a certainly high degree of crosslinking as well as to impart an average axial residual compressive stress of about 3 MPa to the Terfenol-D particulate chains through the thermal shrinkage of the Spurr epoxy in the MC [14]. This built-in residual compressive stress was showed to be effective in creating a preferred non-180° domain state in the as-prepared MC similar to the case of applying an external prestress to assert an initial non-180° domain state in monolithic Terfenol-D MA [14,15]. In fact, magnetostrictive materials with an enhanced motion of non-180° domain walls were found to have an increased deformation contribution and hence an enhanced magnetostrictive strain capability [11–15]. After demolding, the MC was cut and lapped into bar-shaped samples of length 25 mm, width 4 mm and height 4 mm. The Terfenol-D particulate volume fraction of the MC bars was determined to be 0.51 based on Archimedes' principle and rule-of-mixture formulation for density expressed below:

$$\rho_c = v_f \rho_a + (1 - v_f)\rho_e, \quad (1)$$

where ρ_c, ρ_a, and ρ_e are the densities of the MC bars, Terfenol-D particles (=9250 kg/m^3), and Spurr epoxy (=1102 kg/m^3), respectively; and v_f is the Terfenol-D particulate volume fraction of the MC bars.

The FBG was fabricated in a standard telecommunication optical fiber (Corning SMF-28) using a phase mask with a pitch of about 1 μm. A 248 nm excimer laser was used to transfer the periodic pattern of the phase mask onto the 9 μm core of the optical fiber by modulating the refractive index along the fiber core with a length of 6 mm. A light traveling through a FBG with a Bragg wavelength (λ_B) will be reflected according to the following relationship:

$$\lambda_B = 2\, n_{\text{eff}} \Lambda, \quad (2)$$

where n_{eff} is the effective refractive index of the fiber core and Λ is the periodic spacing of the FBG (note that 2Λ is the pitch of the phase mask). When a FBG is subject to an applied strain (ε), both n_{eff} and Λ change, resulting in a shift in λ_B. The ε-induced Bragg wavelength shift ($\Delta\lambda_B$) can be expressed as

$$\frac{\Delta\lambda_B}{\lambda_B} = k\varepsilon, \quad (3)$$

where k (~0.78) is the gauge factor and is related to the strain-optical coefficient (p_e) of the optical fiber by $1 - p_e$. In our MC–FBG sensor, this ε is due to the direct coupling of the magnetostrictive strain from the MC bar (Fig. 1).

As the mechanical coupling between the MC bar and the FBG plays a crucial role in the sensitivity and frequency response of the MC–FBG sensor, the FBG was slightly stretched before being glued onto a MC bar at two points on each side of the FBG using a very thin (<10 μm) layer of non-conductive adhesive with sufficient hardness to achieve at least 95% mechanical coupling and to ensure a uniform elongation of the FBG under the stimulus of magnetic fields (Fig. 1). The bonded FBG was about 8 mm in length and had about 90% peak reflectivity. The 3 dB bandwidth and initial peak wavelength of the MC–FBG sensor were 0.241 and 1548.12 nm, respectively, at zero magnetic fields.

3. Performance evaluations

Fig. 2 shows the experimental setup for evaluating the quasistatic and dynamic performances of the MC–FBG magnetic field sensor. The MC–FBG sensor was placed between the pole gap of a C-shaped high-frequency electromagnet, and the whole sensor-electromagnet assembly was situated between the pole gap of a C-shaped, water-cooled, low-frequency electromagnet (Mylten PEM-8005 K) to receive the stimulus of magnetic fields in the longitudinal direction of the sensor (also along the length direction of the MC bar). A C-band amplified spontaneous emission (ASE) source or a tunable laser (Agilent 81640B), combined with a 3 dB coupler, was used to illuminate the MC–FBG sensor via ports 1 and 2 of an optical circulator. The reflected wavelengths via ports 2 and 3 of the optical circulator were split by a 3 dB coupler and then measured by a 125 MHz photodetector (NewFocus 1811) or an optical spectrum analyzer (OSA) (Agilent 86140A) with a 0.1 nm resolution.

In the quasistatic performance evaluation, the low-frequency electromagnet was energized by an electromagnet controller to provide a quasistatic magnetic field (H) with the maximum amplitude of 146 kA/m and a frequency of 1 Hz to the MC–FBG sensor. The ASE source and the OSA were employed to illuminate the MC–FBG sensor and to measure the quasistatic peak wavelength of the sensor due to the direct coupling of the magnetostrictive strain from the MC bar to the FBG, respectively. A strain gauge attached to the center of the MC bar and connected to a strain indicator (not shown) was adopted to acquire the magnetostrictive strain of the MC bar. It is noted that a tunable optical filter and a photodetector

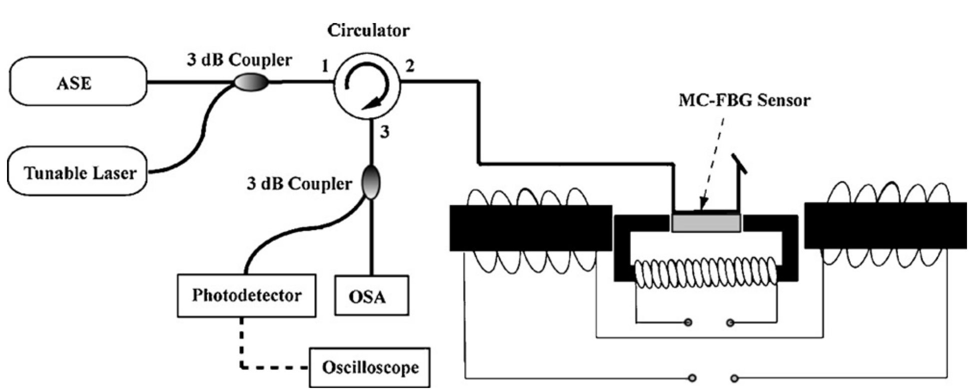

Fig. 2. Experimental setup for evaluating the quasistatic and dynamic performances of the MC–FBG magnetic field sensor.