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D-shaped tilted fiber Bragg grating using magnetic fluid for magnetic field sensor

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ABSTRACT

In our work, a numerical investigation of a magnetic field sensor based on a D-shaped tilted fiber Bragg grating and magnetic fluid is performed. The sensing probe is constructed by placing the magnetic fluid film on the flat surface of the D-shaped tilted fiber Bragg grating. We investigate the resonance wavelengths of the proposed structure with different tilted angles of grating ranging from 0° to 20°, and analyze the magnetic field sensing characteristics. The simulation results show that the optical fiber sensor exhibits optimal transmission characteristics with a tilted angle of 8°. The wavelength sensitivity of the magnetic field sensor is as high as −0.18nm/Oe in the range of 30Oe–270Oe, and it demonstrates a linearity up to $R^2 = -0.9998$. Such sensor has potential applications in determining magnetic sensing field.

1. Introduction

Optical fiber sensing technology has the advantages of small size, broad dynamic range, resistance to electromagnetic interference, etc., and is widely studied by researchers [1–3]. In the past few years, optical fibers have been used in magnetic field detection, and various kinds of optical fiber magnetic field sensors have been developed [4–6]. In the optical fiber sensing field, some combinations of magnetically sensitive material have been particularly well-researched due to their advantages of low cost, fast response and high sensitivity. Typical varieties of optical fiber magnetic field sensors include photonic crystal fibers filled with magnetic fluid [7], D-shaped fibers based on magnetic fluid film deposited on the flat face of the fiber [8], tapered thin-core fibers combined with magnetic fluid [9], and singlemode–multimode–singlemode fibers using magnetic fluid as cladding [10]. Improved magnetic field sensing properties such as sensitivity, selectivity and response speed can be achieved using these fiber structures. However, these optical fiber sensors have two shortcomings. The first is related to the absorption of transmitted light. The transmitted optical signal is greatly attenuated because the magnetic fluid has a large coefficient [11]. The second problem is with the response at high magnetic fields. The sensor is based on the magnetic tenability of refractive index of the magnetic fluid. However, there is no obvious change in the refractive index when the magnetic field is above 90 Oe [12]. As such, it is necessary to design a novel optical fiber magnetic field sensor which can address these issues.

Tilted fiber grating, as a special fiber mode, was first presented by Meltz G. in 1990 [13] and has since been extensively studied by researchers. Compared with common fiber gratings, the grating stripe of the structure is tilted by less than 90° relative to the optical axis. The cladding and core modes exhibit the same response to environmental changes. Due to this characteristic, many tilted fiber gratings were reported to be able to monitor magnetic field signal. In 2013, Lin W. reported a theoretical model of a two-dimensional magnetic field vector sensor [14]. In this paper, the optical transmission characteristics of the sensor as a function of rotation angle and magnetic field intensity were analyzed in detail. The results showed that the transmission decreases as the rotation angle increases from 0 to 90 °, and furthermore it exhibits an increasing trend as the magnetic field is increased. In 2014, Yang D. proposed a magnetic field sensor based on a tilted fiber grating [15]. The grating-containing sensor probe was fabricated by inserting the magnetic fluid into a capillary tube. The results showed that the resonant wavelength was shifted by 106 pm when the magnetic field was increased to 32 mT. In 2015, Miao Y. investigated an intensity-interrogated magnetic field sensor combining magnetic fluid and tilted long-period fiber grating [16]. The transmission losses of the resonance wavelength were studied. The results demonstrated a sensitivity of 0.05 dB/Oe^{-1} in the magnetic field range of 75 Oe–300 Oe. The sensor

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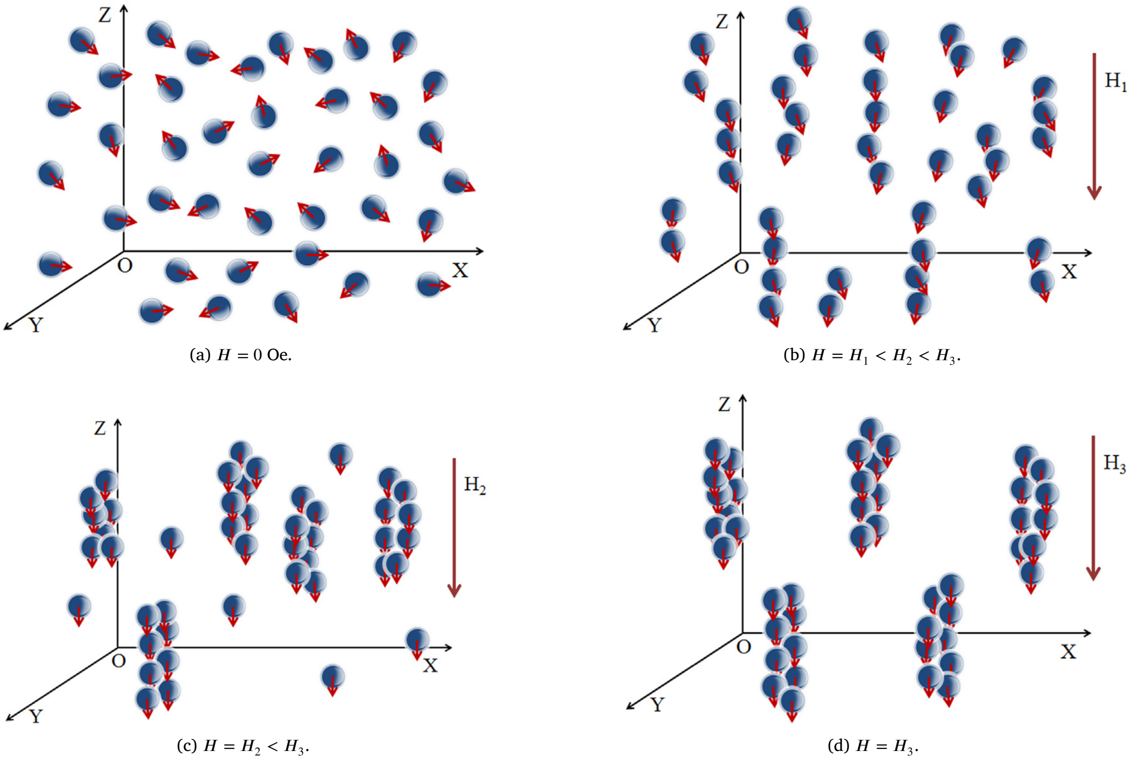

(a) $H = 0$ Oe.

(b) $H = H_1 < H_2 < H_3$.

(c) $H = H_2 < H_3$.

(d) $H = H_3$.

Fig. 1. Microstructure change of magnetic fluid with an increasing magnetic field.

reported in this paper exhibited good magnetic sensing characteristics, but there were still some problems with the tilted angle, linearity and transmissivity, which needed to be addressed.

In our work, we propose a magnetic field sensor probe fabricated by depositing a magnetic fluid film on the flat surface of a D-shaped tilted fiber Bragg grating. In order to analyze this sensor model carefully, the transmission characteristics of the core mode and cladding mode in response to the tilted angle were investigated. The wavelength difference between the Bragg resonance peak and cladding resonance peak could be tuned by changing the external magnetic field. This allows the probe to function as a magnetic field sensor through detecting the change in the wavelength difference.

2. Sensing principle

The magnetic field sensor functions by combining a magnetic fluid film and D-shaped tilted fiber Bragg grating. In this section, the theoretical model of the magnetic fluid microstructure is first introduced, and then the structure and principle of the magnetic field sensor probe are described.

2.1. Theoretical model of magnetic fluid microstructure

Magnetic fluid, as a novel optical functional material, is a stable magnetic colloid composition of magnetic particles coated with surfactant dispersed in a carrier liquid [17]. The magnetic material is usually inserted into a film when being used for sensing a magnetic field [18–20].

Fig. 1 depicts the motion of magnetic particles in increasing magnetic fields. Each magnetic particle can be seen as a single-domain particle. In the absence of magnetic field, the magnetic particles are randomly distributed in a carrier liquid (Fig. 1(a)). In this process, the particles move due to Brownian motion, and separate from each other by repulsion force. In the presence of a low magnetic field, many particles have a tendency to arrange along the direction of the applied magnetic field (Fig. 1(b)). With further increase of the magnetic field, some magnetic columns are formed. Several particles remain suspended in the carrier liquid (Fig. 1(c)). When the magnetic field is increased beyond a certain value, the suspended magnetic particles disappear (Fig. 1(d)). It can be concluded from Fig. 1(c) and (d) that solid–liquid separation occurs due to the aggregation of the magnetic particles. Similarly, the microstructure of the magnetic fluid can be magnetically tuned by decreasing the magnetic field. With decreasing magnetic field, the effect of magnetic field on the magnetic particles is weakened, and several particles separate from the magnetic columns. With a continued decrease of magnetic field, the magnetic columns break into a few magnetic chains, because the effect of the Brownian force is greater than the effect of the applied magnetic field. When the applied magnetic field is reduced to zero, the magnetic particles reach the final dissociated state. The reversible change in the magnetic fluid microstructure leads to a change in its optical properties, which can be used in optical sensors.

The optical properties of a magnetic fluid can be modulated due to the two-phase separation. Refractive index, a fundamental optical property, can be changed by the applied magnetic field, and the parameter $n_{\mathrm{MF}}(H,T)$ is expressed as [21]

$$n_{\mathrm{MF}}(H,T) = \left[n_s - n_0\right]\left[\coth\left(\alpha\frac{H - H_{c,n}}{T}\right) - \frac{T}{\alpha\left(H - H_{c,n}\right)}\right] + n_0, \quad (1)$$

Where $H_{c,n}$ denotes the magnetic field value when magnetic chains are just formed, n_0 denotes the refractive index of magnetic fluid in a magnetic field of less than $H_{c,n}$, n_s denotes the refractive index in the state of magnetic saturation. T denotes the temperature in Kelvin, H denotes the applied magnetic field, and α denotes the fitting parameter.

It can be calculated from Eq. (1) that the effective refractive index increases with increasing magnetic field. In our work, magnetic fluid with a volume fraction (percentage volume of particles relative to the volume of the solution) $\Phi = 1.46\%$ was used as the magnetically sensitive material. Fig. 2 depicts the increasing magnetic fluid refractive index with increasing magnetic field [20]. In the magnetic field range of 30 Oe–270 Oe, the refractive index increases, but the slope gradually