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Magnetic field sensor based on magnetic-fluid-coated long-period fiber grating

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Abstract

Magnetic fluid is a promising material for sensing applications due to its remarkable magneto-optic properties. An optical fiber magnetic field sensor was developed using a long-period grating (LPG) coated with magnetic fluid. Magnetic fluid undergoes magnetization, aggregation, and phase transitions when it is under an external magnetic field. Optical properties changes that induced by the magnetic field can be sensed by the LPG of which resonant wavelength and transmission minimum are highly sensitive to the change of ambient medium. We demonstrate that the proposed sensor can maintain a high sensitivity of ~0.154 dB/Gauss at field strength of as low as ~7.4 Gauss.

Keywords: fiber optics sensors, magnetic fluid, long period fiber gratings

1. Introduction

Magnetic fluid is a colloidal suspension in which magnetic nanoparticles are coated with surfactant. It has attracted many investigation activities due to its remarkable magneto-optic effects, such as tunable refractive index, birefringence and the Faraday effect [1–3]. Each nanoparticle in magnetic fluid can be considered as a permanent magnet that tends to align with the magnetic field direction due to the dipole–dipole interactions [4–6]. The variation of the microstructure and the corresponding optical properties under external magnetic field make magnetic fluid a promising material to be adopted in magnetic field sensing applications. In recent years, optical fiber based magnetic field sensors have been intensively investigated due to their light weight, compact size and high sensitivity [7]. Gao *et al* proposed a photonic crystal fiber (PCF)-based sensor with a sensitivity of 0.011 μW Oe^{-1} [7]. Chen *et al* achieved a sensitivity of 0.748 dB mT^{-1} by using the structure of single-mode–multimode–single-mode [8]. Wang *et al* also suggested a sensor based on single-mode–multimode–single-mode and a sensitivity of −16.86 pm Oe^{-1} was obtained [9]. Miao *et al* proposed an S-tapered fiber based sensor and a sensitivity of 1.3056 dB mT^{-1} was achieved [10]. Lin *et al* investigated a sensor based on a typical multimode interferometer and reported a sensitivity of −0.1939 dB mT^{-1} [11]. Owing to the differences among structures of optical fiber and types of magnetic fluid, the measuring ranges and the sensitivities varied from one proposed magnetic field sensor to another. Although many magnetic field sensors based on specific optical fiber structures have been proposed, a sensor that is simply based on long-period grating (LPG) is rarely studied. Compared with above mentioned fiber structures, LPG is favored due to the outstanding sensitivity to ambient environment and the simplicity of configuration for multi-parameter measurement [12–14]. LPG also shows advantages in advanced *in situ* sensing platforms. Zheng *et al* developed a humidity sensor based on interior nanofilm-coated PCF-LPG with high sensitivity and selectivity as well as excellent thermal stability [15]. Highly sensitive and selective moisture detection is also achieved by coating nano-structure on LPG that inscribed on single-mode fiber (SMF)-28 optical fiber [16]. Zhang *et al* demonstrated a highly sensitive sensor based on zeolite-coated LPG for chemical vapor detection [17]. In this paper, we propose a magnetic sensor based on LPG coated with the magnetic fluid, providing with high sensitivity and reduced cost. Our proposed magnetic field sensor possesses a higher sensitivity of ~0.154 dB/Gauss compared to those of previous studies [8, 10, 11] and a low measurement threshold of ~7.4 Gauss.

2. Theory

When a magnetic field is applied to magnetic fluid, magnetic particles tend to align and form needle-like chains along the applied field direction [18]. When the magnetic field gradually increases, more particles are magnetized and join the agglomeration. The short needles formed in magnetic fluid further elongate and evolve into columns [19]. The physical energies involved in the aggregation of the magnetic particles in magnetic fluid under applied magnetic field are thermal energy and magnetic energy [20, 21]. The repulsive forces between those columns lead to a relatively stable hexagonal structure in magnetic fluid when the magnetic field reaches certain strength. Most investigations of the optical properties of magnetic fluid treated the phase of hexagonal columns as the equilibrium structure and viewed the magnetic fluid as saturated.

The fiber core of LPG possesses periodic refractive index perturbation, which couples the fundamental core mode to several forward-propagating cladding modes as long as the phase matching conditions are satisfied [22]. The mode conversion from core mode to cladding modes results in attenuation bands in core mode transmission spectrum centered at discrete resonant wavelengths which satisfy the phase matching condition [23]

$$\lambda_{\mathrm{p}} = \left(n_{\mathrm{core}}^{\mathrm{eff}} - n_{\mathrm{p,clad}}^{\mathrm{eff}}\right)\Lambda, \qquad (1)$$

where λ_{p} is the resonant wavelength of pth order cladding mode, $n_{\mathrm{core}}^{\mathrm{eff}}$ is the effective index of core mode, $n_{\mathrm{p,clad}}^{\mathrm{eff}}$ is the effective index of pth order cladding mode and Λ is the grating period. Hence the resonant wavelength of LPG is dependent on the difference between the effective refractive indices of core mode and cladding modes, which can be modulated by the surrounding refractive index of LPG [24].

The transmission minimum, or the resonant dip of LPG is a function of coupling constant κ and grating length L. It is proportional to $\cos^2(\kappa L)$. The coupling constant κ decreases with increasing external perturbation, such as ambient refractive index, bending and transverse load [25]. For a saturated LPG with transmission minimum located at the lowest point, or the 'valley' of $\cos^2(\kappa L)$ curve, the transmission minimum goes up with the ascending $\cos^2(\kappa L)$ curve as the coupling constant reduces. On the other hand, for an over-coupled LPG with transmission minimum corresponds to the point far from the 'valley', the resonant dip becomes stronger with the downward $\cos^2(\kappa L)$ curve as the coupling constant decreases.

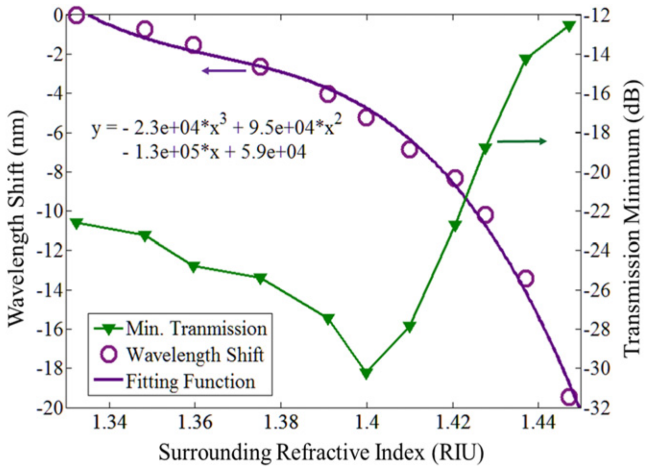

Figure 1. Wavelength shift of LPG against ambient refractive index.

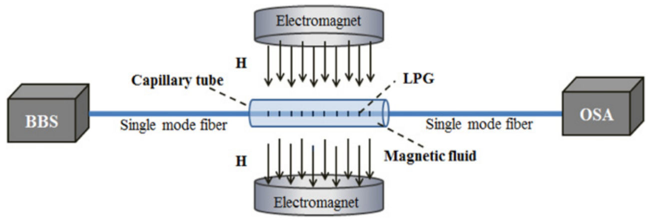

Figure 2. Experimental setup of the proposed magentic field sensor.

3. Results and discussion

The LPG used in the experiment is written on a standard SMF using the ultraviolet irradiation method. It has a grating period of 450 μm and a grating length of 30 mm. The resonant wavelength that corresponds to the highest order of the cladding mode satisfying the phase matching condition of the LPG is at 1590.8 nm. First, we calibrate the refractive index response of the LPG. The LPG is immerged into refractive index matching liquids, which are the mixture of glycerol and water with different volume concentrations. The refractive indices of the matching liquids range from 1.3323 to 1.4472. As predicted from equation (1), the resonant peak gradually shifts to shorter wavelengths as the surrounding refractive index increases (figure 1). The shift of resonant wavelength of LPG against increasing ambient refractive index fits well with the cubic function $y = -23\,300x^3 + 95\,455x^2 - 130\,400x + 59\,400$.

The resonant dip becomes stronger when ambient index increases from 1.3323 to 1.3998 while becomes weaker when index varies from 1.3998 to 1.4472. This is because the transmission minimum of LPG varies as a function of $\cos^2(\kappa L)$. The transmission minimum first reduces with increasing ambient index, which corresponds to decreasing coupling constant, till it reaches the 'valley' of the $\cos^2(\kappa L)$ curve, at which the LPG coupling is saturated. As the coupling constant further reduces, the resonant dip goes up along with the ascending $\cos^2(\kappa L)$ curve [25].

The experiment setup for the proposed magnetic field sensor is illustrated in figure 2. The LPG is sealed in a

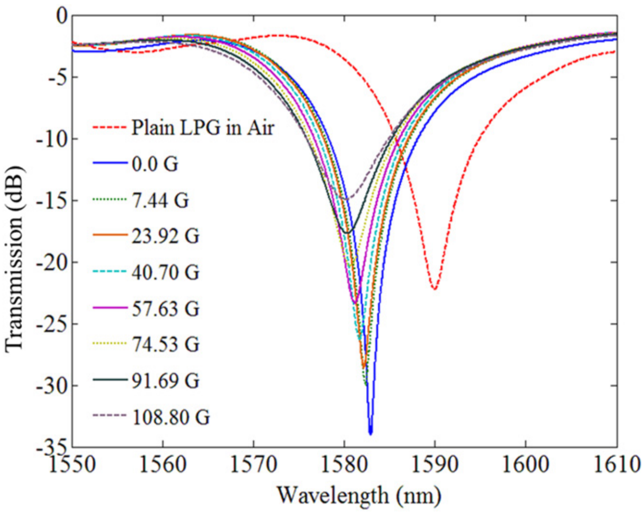

Figure 3. Spectrums of LPG under magnetic field.

capillary tube that is filled with magnetic fluid. The diameters of the LPG and the capillary tube are 125 and 450 μm, repectively. The magnetic fluid used in the experiment is EMG605, which is a water-based translucent suspension of magnetite (Fe_3O_4) particles with a volume concentration of 3.9%. The nominal diameter of magnetite particles is 10 nm. The distance between the pair of electromagnet (EM4-HVA LakeShore) is fixed at 15 cm during the experiment. The field strength at the middle point in between the magnets is measured by a gaussmeter (Model 425, Lake Shore). Before the sealed LPG is subjected to the magnetic field, the field strength is set to ~700 Guass first and the temperature between the pair of magnets is monitored for 40 min. It is found that the temperature varied within the range from 23.9 to 24.4 °C. Studies conducted by Hu *et al* and Chaubey *et al* showed that the thermal sensitivities of their adopted LPGs were 47.4 pm $°C^{-1}$ and 0.06 nm $°C^{-1}$ respectively [26, 27]. Chen *et al* reported the thermo-optical coefficient of magnetic fluid to be no more than 10^{-4} $°C^{-1}$ [20]. Hence we consider the temperature variation of 0.5 °C in our work to be small enough so that the thermal effects on the magnetic fluid optical properties and the LPG behavior could be excluded. After the temperature monitoring, the field strength is adjusted back to 0 and the capillary tube is stabilized between the electromagnets and it is perpendicular to the direction of the magnetic field.

A broadband light source couples light to the fiber and the spectrum of LPG is monitored by the optical spectrum analyzer. The magnetic field strength is gradually increased from 0 to ~110 Gauss. Figure 3 shows the variation of the LPG spectrum as the field strength increases. The red dashed line in figure 3 is the spectrum of the bare LPG surrounded by air, of which the resonant wavelength is 1590.8 nm. When the LPG is immersed in magnetic fluid with no magnetic field applied (blue solid line), the resonant wavelength shifts from 1590.8 to 1582.9 nm, and resonant dip significantly enhanced by ~12.5 dB. Based on the fitting function in figure 1, we can estimate that the refractive index of magnetic fluid is ~1.39, which agrees reasonably well with that of a previous study in which the same type of magnetic fluid was used [2].

Then we gradually increase the applied field strength from 0 to ~110 Gauss. The resonant wavelength of LPG undergoes a blueshift from ~1583 to ~1580 nm, as shown in figure 3. We can estimate that the refractive index of magnetic fluid increases from ~1.39 to ~1.41. This trend is in accordance with previous studies that the refractive index of magnetic fluid increases with enhancing field strength [20, 21]. The rise of refractive index is attributed to the phase transition caused by the enhancing magnetic field strength. It has been proven that when the nanoparticles in magnetic fluid cluster into columns, the refractive index of magnetic fluid increases [28, 29]. Hence the magnetite particles gradually agglomerate into chain-like clusters when the field strength increases. Besides, we can observe a ~19 dB reduction of the resonant peak depth from 0 to ~110 Gauss. This significant increase of the transmission minimum is due to the increasing refractive index as well as absorption and scattering effects of magnetic fluid on the evanescent field caused by the formation of aggregations [8, 30], since the absorption and scattering effects that correspond to the complex index of magnetic fluid incur loss in cladding mode, so the cladding mode resonance is reduced accordingly [31]. Our LPG is slightly over-coupled according to figure 1. Therefore, as the surrounding material changes from air to magnetic fluid with index of ~1.39, the resonant dip enhances and varies to the 'valley' or a slightly 'under-coupled' position [25]. Then the dip moves up following the upward $\cos^2$ (κL) curve as the applied magnetic field strength increases since the refractive index as well as the absorption and scattering effects of magnetic fluid are increasing, which correspond to increasing external perturbation and also reducing coupling constant. Slightly different from figure 1 that the 'valley' occurs at index of ~1.40, the 'valley' or the slightly 'under-coupled' position in figure 3 is at ~1.39. This is due to the different surrounding materials used in the two cases. Figure 1 corresponds to the variation of LPG when it is surrounded by refractive index liquid while figure 3 corresponds to the situation where LPG is surrounded by magnetic fluid, which affects the external perturbation of LPG not only by the increased refractive index but also by the enhanced absorption and scattering effects. Due to the additional absorption and scattering effects of magnetic fluid, the 'valley' or the saturation point of LPG occurs at a slightly smaller index.

Figure 4 shows the nearly linear decrease of resonant wavelength and the linear and steep increase of minimum transmission of LPG. The wavelength shift eases as the field strength approaches ~110 Gauss, which indicates the saturation of phase transition in magnetic fluid [20]. According to the fitting function of minimum transmission, our proposed sensor provides a high sensitivity of ~0.154 dB/Gauss.

The measurement range of each type of magnetic field sensor is normally limited by the threshold value in which the sensor starts to response to external magnetic field. It can be seen in figure 3 that there is an obvious response of LPG spectrum even when the field strength is as small as

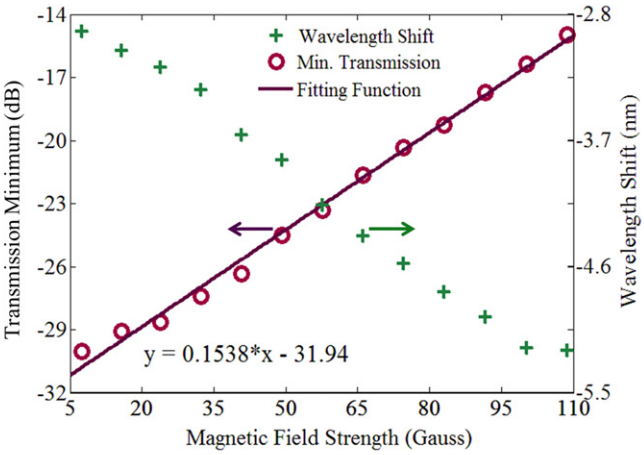

Figure 4. Wavelength shift and transmission minimum of LPG under magnetic field.

~7.4 Gauss. Therefore, magnetic-fluid-coated LPG shows promising applications in low field measurement compared to other configurations.

4. Conclusions

A magnetic field sensor based on magnetic fluid coated LPG is investigated. The magnetic field measurement is achieved by monitoring two parameters, the wavelength shift of the attenuation band and the variation of transmission minimum of LPG. Our proposed magnetic field sensor shows advantage of high sensitivity for low field strength measurement.

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