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Optical fiber magnetic field sensor based on magnetic fluid and microfiber mode interferometer

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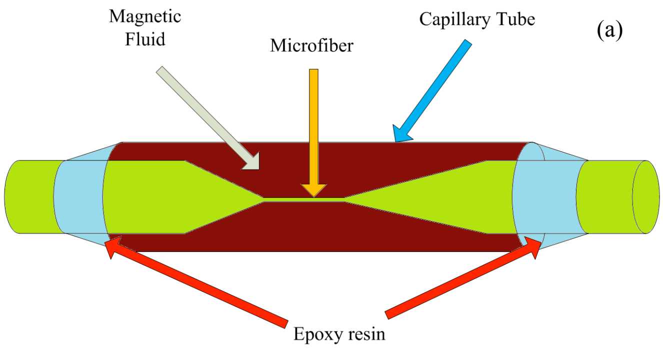
ABSTRACT

A magnetic field sensor is proposed based on the combination of magnetic fluid (MF) and an optical microfiber mode interferometer (MMI). It is measured that the MMI is highly sensitive to ambient refractive index (RI) with a high sensitivity up to 16539 nm/RIU while RI of the MF is changeable with external magnetic field strength. By monitoring wavelength shift of transmission spectrum of the MMI, magnetic field measurement is realized with a maximum sensitivity of -293 pm/Oe in the range of 0-220 Oe.

1. INTRODUCTION

Recently, optical fiber magnetic field sensors using magnetic fluid (MF) as sensing material have been widely studied. MF is a kind of highly stable colloidal material with magnetic nanoparticles dispersing evenly in a suitable liquid carrier such as water and ester. Owing to the variety of magneto-optical properties such as Faraday effect, tunable refractive index (RI), field dependent transmission and birefringence, MF have attracted considerable research interest as a sensing material in magnetic field sensor development [1-4]. Some of the reported schemes for MF-based magnetic field sensors are realized by coating MF on the surface of various optical fiber devices, including interferometers [5-10], fiber gratings [3, 11-13] and microfiber knots [14], and measurement of magnetic field is achieved through the effect of changeable RI of the MF with magnetic field. However, the response of RI of MF to external magnetic field change is usually quite weak (~0.02 RIU for 1661 Oe of magnetic field strength change [3]). Therefore, sensitivities of these MF-coated fiber magnetic field sensors is relatively low, normally less than 100 pm/Oe. By injecting MF into air holes of photonic crystal fibers (PCFs) or Fabry-Perot cavity, relatively high sensitivity (up to 1.9 nm/Oe) can be achieved [15-17], but the sensor fabrication are much more difficult and the PCFs are usually expensive.



(b)

Fig. 1. (a) Schematic diagram of the proposed magnetic field sensor.
(b) Optical microscope image of the MMI.

Microfiber mode interferometer (MMI) is an excellent optical fiber-based RI sensor that was developed recently [18-21]. It shows higher sensitivity to external RI than normal optical fiber interferometers because of their much smaller diameter and larger evanescent field. In this paper, we demonstrate a highly sensitive, compact and low cost optical fiber magnetic field sensor by using a MMI which is coated by MF. Magnetic field strength measurement with high sensitivity up to -293 pm/Oe is achieved by detecting transmission spectrum of the MMI.

2. SENSOR FABRICATION AND PRINCIPLE

A schematic diagram of the proposed magnetic field sensor is shown in Fig. 1 (a). It includes an optical fiber taper-based MMI encapsulated in a silica capillary tube. The MMI was simply fabricated by tapering a single-mode fiber using a fusion splicer (Fujikura, FSM-100P) with optimized motor moving speed, arc power and finishing time. An optical microscope image of the MMI is shown in Fig. 1 (b). It contains a 2.7-mm long microfiber with waist diameter of ~7 μm and two abrupt transitions in the tapering region of the sing-mode fiber. The MMI was then fed into the capillary tube with an inner diameter of 1 mm and a length of 30 mm from one fiber end and straightened by two fiber clamps. The capillary tube was moved along the MMI to cover the tapering region of the MMI well at the center. A vertical translation stage was then used to support the tube and to locate the fiber at the center of the tube. After being filled with MF by using an injector, the tube was sealed at both ends with epoxy resin. The MF we used (EMG 607, Ferrotec Inc.) is a highly stable water based ferrofluid containing Fe_3O_4 magnetic nanoparticles of average diameter of ~10 nm. The particle concentration in volume fraction is 1.8% and the saturation magnetization is ~110 Oe.

Since the waist diameter is much larger than 1.1 μm, which was reported to be the upper limit of diameter for a silica wire supporting only single fundamental mode operation at 1.5μm [22], high-order modes can propagate through the microfiber of MMI. When the light enters the first abrupt taper region from the lead-in SMF, a fundamental and a higher order mode are excited due to the waveguide disturbances. They recombine at the uptaper transition and interfere with each other to generate interference. We assume that the effective indices of the two modes are n_1 and n_2 respectively. The phase difference between them is then approximated as $\Phi = 2\pi\Delta nL / \lambda$, where $\Delta n = n_1 - n_2$ and λ is the wavelength in vacuum. The mth dip wavelength λ_m in the transmission spectrum of the MMI can be expressed as $\lambda_m = 2(n_1 - n_2)L / (2m+1)$, where m is the interference order [18-20]. Because n_2 is sensitive to the external RI, the later can be detected by monitoring the transmission dip wavelength variation.

3. EXPERIMENTS AND RESULTS

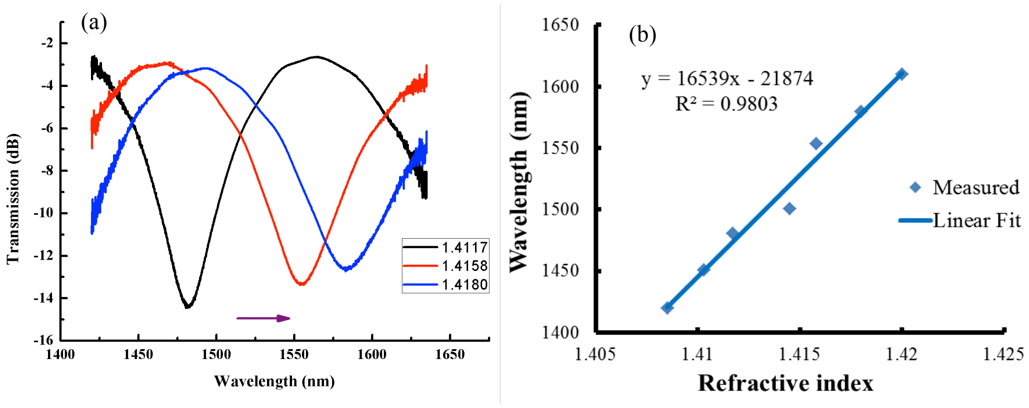


Fig.2 (a) Transmission spectra of the MMI under different RI solutions. (b) Wavelength shift of the resonant dip against RI.

Before sealing the MMI with MF, we measured its response to RI experimentally. Fig. 2 (a) shows three transmission spectra measured when the MMI was surrounded with different glycerol solutions with different concentrations. The transmission spectrum has a significant red shift with RI. The transmission dip shifted from 1420 nm to 1610 nm when RI was changed from 1.4085 to 1.4200. The RI sensitivity of the MMI reaches 16539 nm/RIU, as shown in Fig. 2 (b).

Experimental setup for the magnetic field sensing is shown in Fig. 3. Two ends of the fiber sensor were connected to an optical spectrum analyzer (OSA) (Yokogawa, AQ6370B) and a broadband light source (BBS), respectively. The magnetic field was generated by a permanent magnet with a large cross sectional dimension of 100 mm×50 mm, covering well the sensor head which was center-aligned and paralleled to the emission surface of the magnet. The magnetic field strength was tuned by changing the distance between the sensor head and the magnet surface. A gauss meter was used to measure the magnetic field strength in a real-time manner.

Fig. 4 (a) shows the measured transmission spectra of the proposed sensor under various magnetic field strengths from 0 to 220 Oe. It obviously shows that the transmission tip of the MMI shifts to

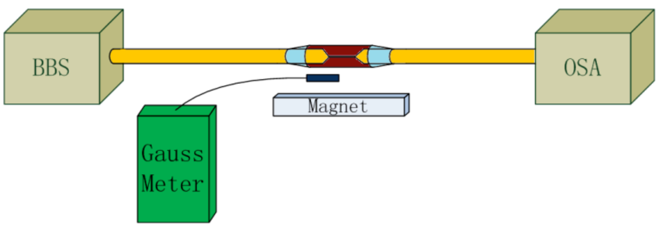


Fig. 3. Experimental setup for sensing measurement.

shorter wavelengths and, at the same time, intensity of the transmission dip reduced with increase of the magnetic field strength. The blue shift of dip wavelength indicates that RI of the MF decreases with magnetic field intensity. That agrees with previous reports where the magnetic field was also applied perpendicularly to the fiber axis [3, 7]. The insert loss shown in Fig. 4(a) is ~10 dB, much larger than that observed in Fig. 2 when the sensor head was surrounded with transparent glycerol solution. That may be related to the high scattering and absorption effects of MF to the evanescent field of optical light travelling in the microfiber.

Fig. 4 (b) shows the measured data of wavelength against magnetic field strength. The dip wavelength shifts quickly from 1584.2 to 1563.7 nm when magnetic field strength is increased from 0 and 71 Oe. After that, the response slow down since the MF is gradually saturated to magnetic field. The corresponding sensitivity in the linear response range is up to -293 pm/Oe, which is much better than the previously reported results (less than 100 pm/Oe) for MF-based fiber interferometer magnetic field sensors [5-14]. We reckon that the much smaller waist diameter of microfiber and the relatively higher particle concentration of the MF contribute to the high sensitivity. For microfiber-based sensors, smaller diameter generally leads to higher sensitivity because the power fraction of evanescent field increases. The diameter of microfiber taper in [7] is 65.5 μm, much larger than that of ours (~7μm). The MF used in [14] (EMG509, Ferrotec) exhibits a lower particle concentration (0.6%) than the one we used (1.8%). A higher particle concentration of MF may lead to relatively larger variations in both RI and scattering-induce loss when the same magnetic field is applied.

The nonlinear response behavior of MF-based magnetic field sensor is inevitable because of the saturation magnetization effect of MF. When the magnetic field with relatively low intensity is applied, the initially evenly distributed nanoparticles in the MF agglomerate and further form chains and magnetic columns along the direction of magnetic field, that changes RI of the MF. When the external magnetic field intensity is close or larger than the saturation magnetization intensity, most nanoparticles agglomerate as magnetic chains already, and therefore, RI of MF will not change any more. Based on the RI value of ~1.416 for the MF without magnetic field, the MMI has a high RI sensitivity of 16539 nm/RIU in this case, that contributes a lot to the high sensitivity for the magnetic

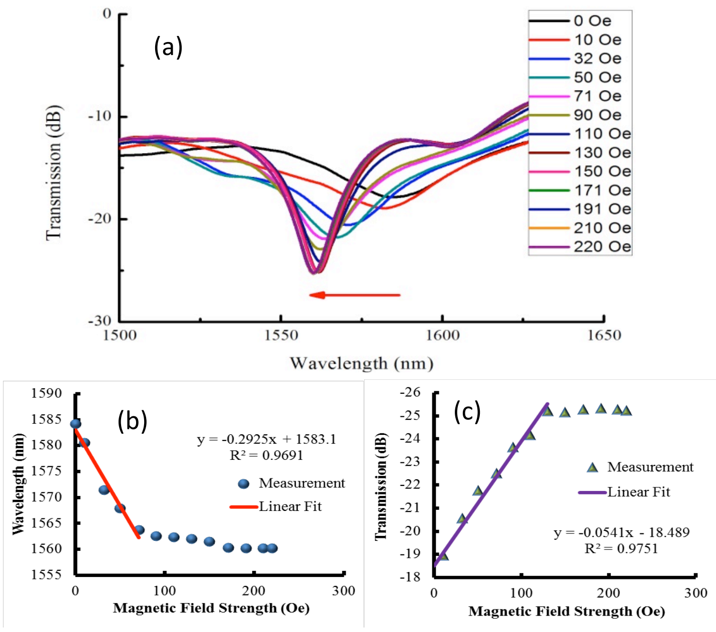


Fig 4 (a) Transmission spectra of the MMI under different magnetic field strength. (b) Dip wavelength shifts under different magnetic field strength. (c) Intensity of transmission dip response to the different magnetic field intensity.

field measurement since the speculated maximum RI change of MF is only ~0.002 RIU.

Fig. 4 (c) shows that the measured intensity of the transmission dip against applied magnetic field strength. It decreases linearly from -17.9 dB to -25.2 dB when the magnetic field strength is changed from 0 to 130 Oe. The sensitivity is 0.054 dB/Oe in this range. The intensity of the transmission dip change is mainly caused by the intensity ratio variation between the two modes. The field-induced RI decrease leads to better confinement of the light within the microfiber, while the losses from scattering and absorption of magnetic nanoparticles in the MF to the fundamental and high-order modes also change due to the field-induced agglomeration effect (chains or columns are formed when the magnetic field become large). The initial intensity difference between the fundamental and high order modes is relatively large because fringe visibility of the interference pattern is only 5.1 dB. It increases from 5.1 dB to 12.4 dB with increasing magnetic field strength that indicates the scattering and absorption effects of MF helped to balance the two modes intensity. Also because of the saturation magnetization of MF, there is a saturated point of magnetic field strength at around 130 Oe, beyond which the transmission dip intensity hardly changes. The two saturation magnetic field strengths are slightly different. That may be caused by the deviation of RI change and nanoparticle agglomeration process in the MF. However it doesn't influence our measurement of magnetic field in the linear response range.

4. CONCLUSION

A magnetic fluid-based magnetic field sensor by using a microfiber mode interferometer has been proposed and experimentally demonstrated. Refractive index, absorption and scattering of magnetic fluid are changed with magnetic field strength owing to the variations of structural pattern of the magnetic nanoparticles in the magnetic fluid. Transmission spectrum of the microfiber mode interferometer is therefore modulated. By monitoring the wavelength shift or the intensity change of the transmission dip, magnetic field strength can be achieved. The sensitivity achieved experimentally are up to -293 pm/Oe and 0.054 dB/Oe for wavelength and intensity measurements, respectively. The demonstrated sensor possesses high sensitivity, low cost and compactness in size.

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