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

Yangzi Zheng [a,b], Xinyong Dong [a,c,d,*], Chi Chiu Chan [b], Perry Ping Shum [d,e], Haibin Su [c,e]

[a] Institute of Optoelectronic Technology, China Jiliang University, Hangzhou 310018, China
[b] Division of Bioengineering, School of Chemical and Biomedical Engineering, Nanyang Technological University, Singapore 637457, Singapore
[c] School of Materials Science and Engineering, Nanyang Technological University, Singapore 639798, Singapore
[d] CINTRA, Research Techno Plaza, 50 Nanyang Drive, Singapore 637553, Singapore
[e] School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

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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 16,539 nm/RIU while RI of the MF is changeable with an 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 a 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.

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

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[*] Corresponding author at: Institute of Optoelectronic Technology, China Jiliang University, Hangzhou 310018, China.
E-mail address: xydong@cjlu.edu.cn (X. Dong).

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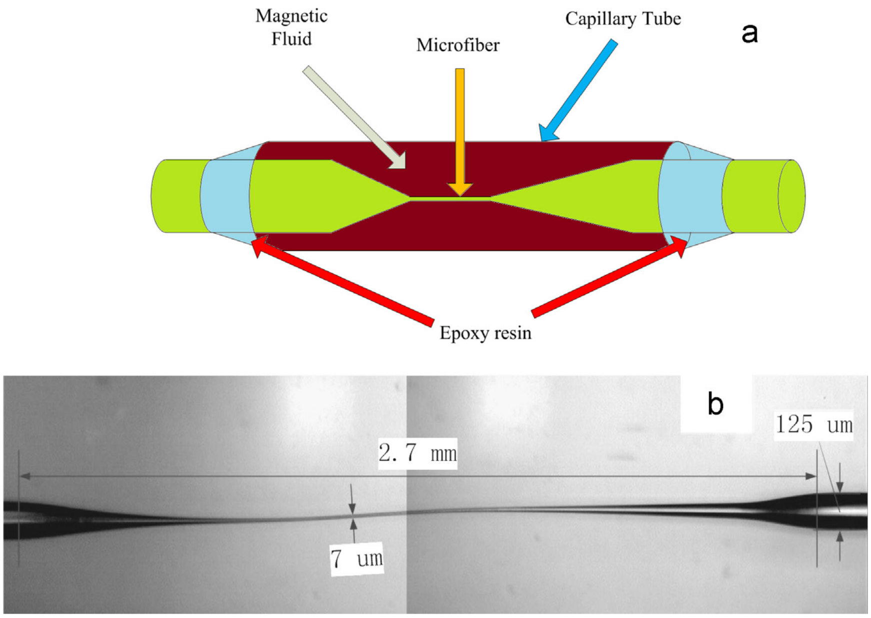

Fig. 1. (a) Schematic diagram of the proposed magnetic field sensor, and (b) optical microscope image of the MMI.

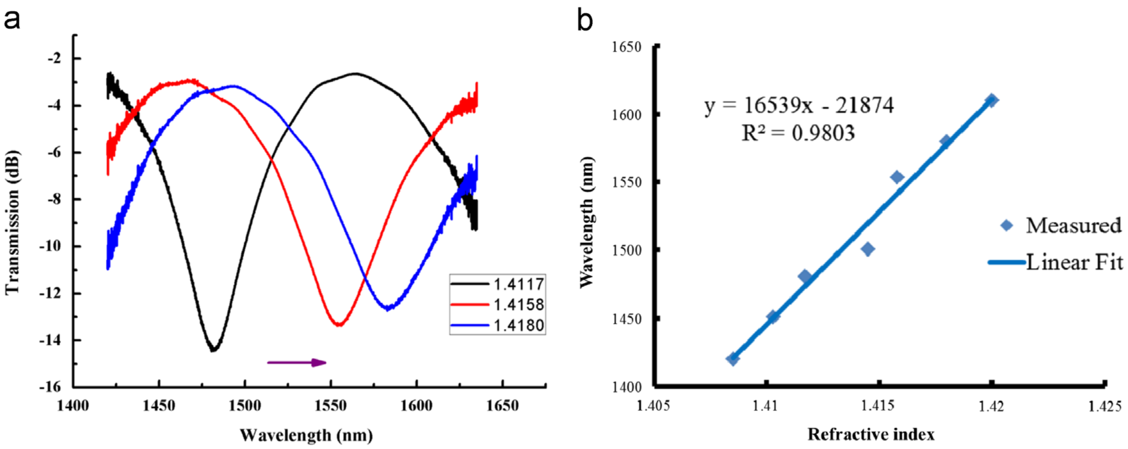

Fig. 2. (a) Transmission spectra of the MMI under different RI solutions. (b) Wavelength shift of the resonant dip against RI.

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 a single fundamental mode operation at 1.5 μm [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

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 redshift 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 16,539 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