Magnetic Field Sensor Based on Nonadiabatic Tapered Optical Fiber With Magnetic Fluid

Azam Layeghi, Hamid Latifi, and Orlando Frazão

***Abstract*— A novel magnetic field sensor using a nonadiabatic tapered optical fiber (NATOF) interacting with magnetic fluid (MF) nanoparticles is proposed and experimentally demonstrated. The NATOF sensitivity when is subjected to refractive index (RI) measurement in the small range from 1.3380 to 1.3510 was 1260.17 nm/RIU as a refractometer sensor. The NATOF is surrounded by a MF whose RI changes with external magnetic field, which MF is as a cladding of tapered fiber. The output interference spectrum is shifted by the change of the applied magnetic field intensity in the range up to 44 mT with a sensitivity of -7.17×10^{-2} nm/mT, used only 0.1% of the volume concentration of MF nanoparticles. This direct manipulation of light with magnetic fields provides an approach to develop future sensors relying on electromagnetic interactions.**

***Index Terms*— Non-adiabatic tapered optical fiber, magnetic field sensor, nanoparticle, Fe_3O_4 magnetic fluid, refractive index.**

I. Introduction

EVANESCENT field is attractive in the field of optical sensing which is based on the partial overlap of the evanescent guided electromagnetic wave with a medium. In particular evanescent-field-based optical fiber sensor has been investigated extensively in the past years [1], [2]. This kind of sensor may have the advantages over conventional one, e.g., more sensitive, on-line analysis, geometrical versatility, remote monitoring, etc. In standard single mode optical fiber (SMF) the amplitude and penetration depth of evanescent field is low which with tapering it can be enhanced. According to method of fabrication of tapered optical fiber, non-adiabatic tapered optical fibers (NATOF) can be designed as highly sensitive structures and they have provided an optical method for detecting changes in refractive index (RI) and biochemical analysis [3]–[5].

Magnetic fluid (MF) is a kind of homogeneous colloidal dispersion of very fine magnetic nanoparticles with diameter in the range of 3-15 nm in suitable liquid carrier with the aid of a molecular layer of surfactant coated on the surface of particles. This prevents the particles from sticking to each other due to van der Waals attraction. MF has been applied to dynamic sealing, damping, cooling in audio speakers and drug delivery in medicine successfully and broadly [6].

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Sensing and measurement of magnetic field is important in geophysics, biology, medicine and industries. Additional motivation for developing a magnetic sensor arises from migratory animals that use the magnetic properties of ferric oxide nanoparticles to navigate with in the earth's magnetic field [7], [8].

The MF is a novel nano-material with diverse magneto-optical effects including Faraday effect, tunable RI, field dependent transmission and birefringence. Nowadays, there are a lot of interest in studying the optical properties and the potential applications to optical devices based on MF with the development of integrated optics and photonic devices due to their many advantages including high sensitivity, high frequency and small size as compared with their conventional competitors [9]. Recently, various optical fiber devices have been developed for magnetic field sensing, by incorporating MF, including the Long Period Gratings (LPGs) [10], etched Fiber Bragg Gratings (FBGs) [11], a two tilted FBGs (TFBGs) [12], and a series of optical fiber interferometers based on PCF [13], Multimode interference [14], the MF film in optical fiber sagnac interferometer [15], microfiber Michelson interferometer [16] and s-tapered fiber sensor [17]. However, most of these sensors have used high concentration of MF. whereas in our experiment we have used low concentration. Additionally, a microstructured optical fiber (MOF) for measuring magnetic field with MF is proposed [18]. Such grating-based sensors require complicated fabrication process and their low RI sensitivity can be improved by cladding etching. Although an ultrasensitive PCF sensor based measuring RI was proposed, it is of yet high cost. Also, the selective inflation of a single hole of a PCF with fluid often is not easy [19]. Among the various optical sensors of magnetic field, NATOF has the distinct advantage of the simple fabrication process and low cost. Additionally, it has relatively controllable and high RI sensitivity [20], [21].

In this letter, a magnetic field sensor based on a NATOF incorporating with low concentration of MF is proposed and demonstrated. To our best knowledge, measuring magnetic field in low concentration of MF has not been reported in the literature. The NATOF sensitivity to RI is high. Since the RI of the MF is sensitive to the magnetic field, the NATOF surrounded with MF is used as a magnetic sensor.

II. Experimental Result

A. Principle of Sensing

The electric susceptibility χ is dependent on the magnitude of the magnetic field and on the relative direction between the

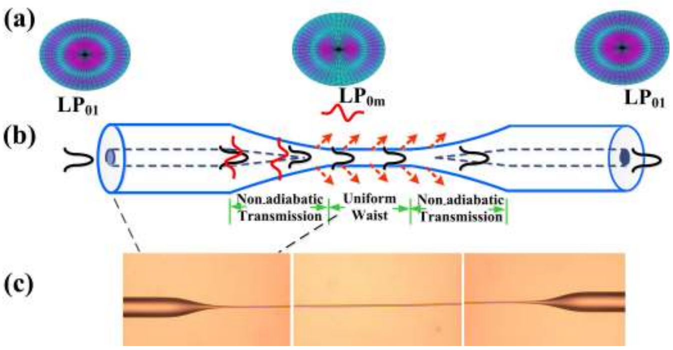

Fig. 1. The NATOF sensor as a Mach-Zehnder. (a) Profile of propagation modes, (b) schematic diagram of the NATOF, and (c) microscope photo of some of the taper.

electric field E and the magnetic field H. When the external magnetic field is perpendicular to the propagation direction of light, we have

$$\partial \chi_{\perp} / \partial H < 0 \tag{1}$$

where $\chi_{\perp}$ is the electric susceptibility. The behaviors of ferromagnetic particles in the MF are dependent on the external magnetic field. So the RI of the MF is shown to be magnetic field dependent. The RI is expressed as $n=\sqrt{\varepsilon_r} = \sqrt{1+\chi}$ where ε_r and χ represent the dielectric constant and the electric susceptibility, respectively. Therefore the RI of MF will decrease when the magnetic field increases [22].

A NATOF operates like a Mach-Zehnder interferometer due to the difference of the optical path between the fundamental core mode and the higher order cladding modes. As shown in Fig. 1, at the NATOF, the fundamental core mode in SMF is partly coupled to the LP_{0m} cladding modes. Passing through the interferometer arm, part of the light traveling inside the cladding is coupled back into the core at the end part of taper. Due to the difference between the propagation constants of core and cladding modes, the device can be considered as modal interferometer is shown in Fig. 1.

The interference signal of an tapered fiber with length of L reaches minimum when the phase difference [20]

$$\Phi = 2\pi \, \Delta n_{eff} L / \lambda_k = (2k+1)\pi \tag{2}$$

Where Δn_{eff}, k, and λ_k are effective RI, interference order, and the maximum attenuation wavelength of the kth order. In the tapered section of the NATOF sensors, the core of the fiber is replaced with clad, such that the effective RIs are difference between the m th cladding modes and LP_{01}. When the surrounding RI is increased by δn, the effective RI of the higher order cladding mode is increased by $\delta n_{eff,cl}$. Because the RI of the lowest order mode tightly confined in the fiber is nearly constant, Δn_{eff} is increased by $\delta n_{eff} \approx \delta n_{eff,cl}$, and the k th attenuation peak wavelength shifts to a longer wavelength by $\delta\lambda$ is [20]

$$\delta\lambda \approx \frac{2L\left(\Delta n_{eff} + \delta n_{eff}\right)}{(2k+1)} - \frac{2L\Delta n_{eff}}{(2k+1)} = \frac{2L\delta n_{eff}}{(2k+1)} \tag{3}$$

In this letter with changing magnetic field intensity, RI of the MF is changed. Therefore, the spectra response of the taper will shift correspondingly by changing of magnetic field intensity.

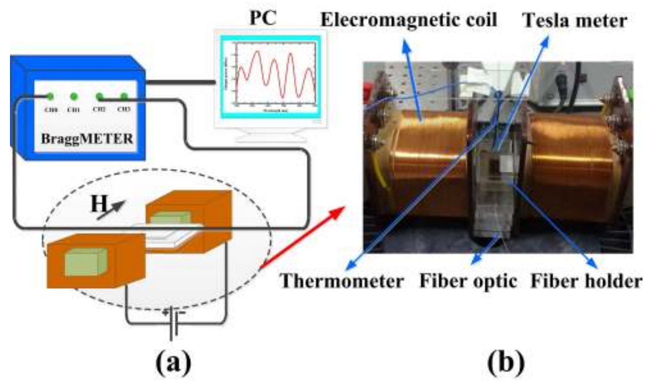

Fig. 2. (a) Schematic diagram of the experiment set up, and (b) a photo of the NATOF sensor inside of electromagnetic field.

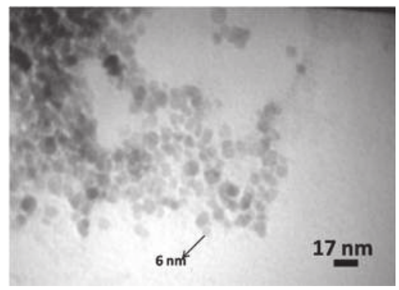

Fig. 3. Transmission electron microscopy image of synthesized Fe_3O_4 nanoparticles.

B. Experimental Setup

In our experiment, the tapered fiber is fabricated using CO_2 laser irradiation on Corning SMF28 fibers [4]. The lengths and the waist diameters of the tapered fibers in our work were in the range of 1.0–1.5 cm and 7–11 μm, respectively. Fig. 2a shows the schematic diagram of the experimental setup for magnetic field measurement with the proposed NATOF sensor. The NATOF is surrounded with MF, and one end of the NATOF is connected to one source channel of the BraggMETER (Fiber Sensing, FS2100), and the other end is connected to one detector channel of BraggMETER with the resolution of 1 pm and the data are analyzed by computer.

The waist region of the NATOF is placed in the middle of the poles of the electromagnet, which generates a uniform magnetic field in the waist region of the NATOF and perpendicular to the fiber axis. The strength of the magnetic field is adjusted by tuning the magnitude of the supply current, and calibrated by a teslameter (Lybold, 516 62).

In this experiment water-based Fe_3O_4 as ferromagnetic nanoparticles was used with the size of approximately 5–10 nm. Fig. 3 shows a transmission electron microscopy image (TEM) of synthesized nanoparticles. The volume concentration of the MF was only 0.1% and Trisodium citrate dihydrate is mixed in the solution as surfactant.

As it can be seen in Fig. 2b, the taper was fixed under tension in the fiber holder. During the tests the temperature of the solution was kept approximately constant about 25 °C. Therefore, during the test, the NATOF showed no cross sensitivity to temperature and strain.

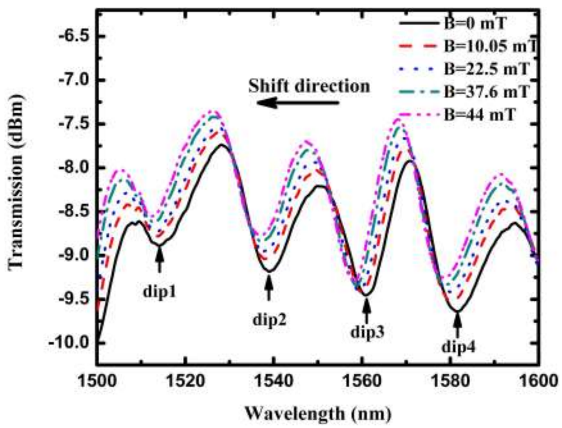

Fig. 4. Transmission spectrum of sensor versus of magnetic field in range from 0 mT to 44 mT.

C. Results

To measure the sensitivity of our tapered fibers to the magnetic intensity, fiber holder was put in the magnetic field and wavelength shift was measured with applying different magnetic field. Fig. 4 shows a typically wavelength shift of the NATOF interferometry spectrum with the increasing of magnetic field from 0 to 44mT. As magnetic field increases, the transmission wavelength of the NATOF shifts to short wavelength, which is consistent with the reduction of RI of MF under increasing magnetic field. There is 1.1 nm wavelength shifts when external magnetic field intensity is changed from 0 to 10.05 mT for dip 4.

When the external magnetic field is perpendicular to the propagation direction of light, according to Eq. (1) the RI of MF will decrease with increasing the magnetic field strength. The total internal reflections of light in tapered section increase. So the amount of loss decrease and the intensity is increased [23], [24].

In order to determine the number and power distribution of the modes that contribute to the interferometry spectrum in Fig. 4, Fast Fourier Transform (FFT) was used to obtain the corresponding spatial frequency spectrum, as shown in Fig. 5. The relationship between the spatial frequency and the interferometer length as well as the modal group index is given by [24], [25]

$$\xi = \frac{1}{\lambda_0^2} \Delta n_{eff} L \tag{4}$$

Where λ_0 is the center wavelength, ξ is the spatial frequency, L is optical length, and Δn_{eff} is the differential modal group index. For a fixed length, a smaller ξ correspond to a smaller Δn_{eff}, which means a lower-order cladding mode [24], [25]. It shows that the power is primarily distributed in the fundamental core mode and the first cladding mode, thus the interference between these two modes play a dominant role for all different magnetic intensity.

Fig. 6 shows the plots of the wavelength shift of different dips versus the magnetic field intensity. It is apparent that, in all cases, dips are linearly shifted towards shorter wavelength as the magnetic intensity increases, which implies that the index of the surrounded MF decrease with the applied magnetic field according to the NATOF coupling theory.

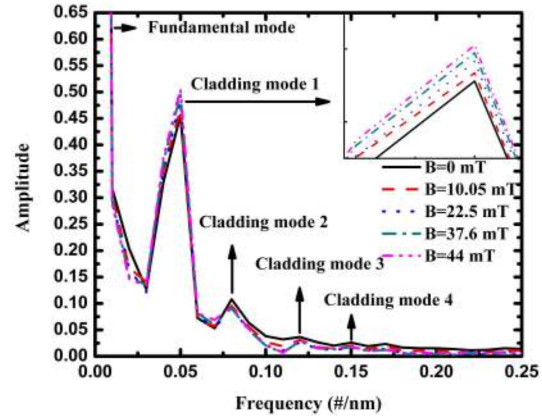

Fig. 5. Spatial frequency spectrum of the NATOF.

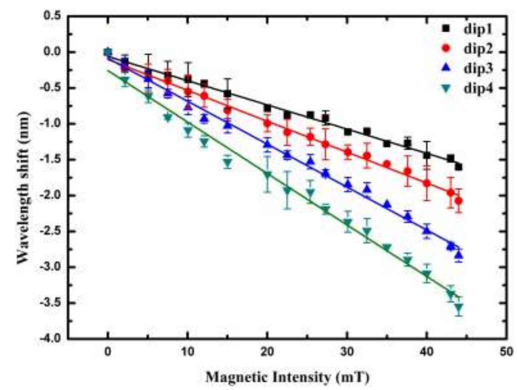

Fig. 6. Wavelength shift versus Magnetic intensity for dip 1, dip 2, dip3, and dip 4.

Each experiment was repeated three times, and averaged, being obtained a maximum error bar for the measured wavelength shifts of ± 0.2 nm. The calibration curves obtained allowed estimating sensitivities of -3.37×10^{-2} nm/mT, -4.31×10^{-2} nm/mT, -5.98×10^{-2} nm/mT, and -7.17×10^{-2} nm/mT for dip 1, dip2, dip3, and dip4, respectively. Comparing the sensitivities obtained in dip2, dip3, and dip 4 with dip1 an enhancement of 28%, 77%, and 113% can be estimated, respectively. This sensitivity enhancement agrees with the fact that the lower interference order (dip4 which has the highest wavelength) is typically more sensitive to RI, according Eq. (3) [20], [21].

Using the experimental data, the RI of the field-dependence of MF can be calculated. The sensitivity of the NATOF for RI in range from 1.3380 to 1.3510 was obtained to be 835.12 nm/RIU, 1081.93 nm/RIU, 1212.50nm/RIU, and 1260.17 nm/RIU for dip 1, dip 2, dip3, and dip4, respectively (Fig. 7).

With the aid of the RI sensitivity and the magnetic field sensitivity of NATOF typically for dip3 in near 1560nm, RI of the MF was calculated as explained in ref. [4] and shown in Fig 8. At the absence of magnetic intensity, the intercept value shows the RI of water-based MF, which has surfactant.

This figure is not limiting values as sensitivity of the NATOF sensor. To improve the sensor's performance, the magnetic fluid's refractive index should be optimized by changing the characteristics of solute. Magnetic fluid's RI has relationship with the surfactant, solvent, solute, and their

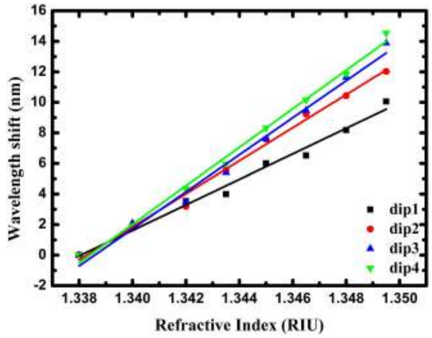

Fig. 7. Wavelength shift versus RI of NaCl solution for dip 1, dip 2, dip3 and dip 4.

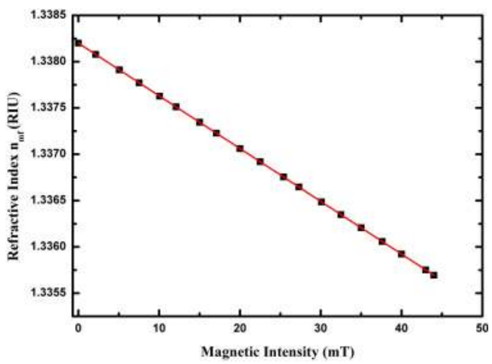

Fig. 8. Refractive index of MF versus magnetic intensity.

quality ratio [11], [26]. Also increasing the taper length and decreasing its waist diameter can enhance the sensitivity.

III. Conclusion

A single mode NATOF sensor has been designed and fabricated to sense the magnetic field using MF. The sensor is surrounded by the MF as the cladding of the NATOF. Appling the external magnetic field, the RI of the MF is changed. The sensitivity of the NATOF sensor for refractive index (RI) measurement in the range from 1.3380 to 1.3510 was 1260.173 nm/RIU as a refractometer sensor. The wavelength shift of NATOF with diameter of about 5 μm is 2.8 nm when the magnetic field increased from 0 to 44 mT. The sensitivity of the NATOF for magnetic field measurement with low concentration of MF was -7.17×10^{-2} nm/mT as a magnetic field sensor, which is ~24 times greater than etched FBG [11] and is ~9 times greater than LPG [10] by using water-based MF with volume fraction of 2% and concentration of 1.2 g/ml. The RI of the MF in this rang of magnetic field was calculated to be from 1.337 RIU to 1.327 RIU. It is worth noticing that the sensitivity of NATOF sensor can be further enhanced by optimizing the RI of the water-based MF, increasing taper length, and decreasing taper diameter.

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