Reflective all-fiber magnetic field sensor based on microfiber and magnetic fluid

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Abstract: A kind of reflective all-fiber magnetic field sensor based on a non-adiabatically tapered microfiber with magnetic fluid is proposed and experimentally demonstrated. The modal interference effect is caused by the abrupt tapers, which result in an approximately sinusoidal spectral response. The reflection spectra of the proposed sensor under different magnetic field strengths have been measured and theoretically analyzed. The maximum sensitivity of 174.4 pm/Oe is achieved at wavelength of around 1511 nm. Besides, an intensity tunability of $-0.02$ dB/Oe is also achieved. Comparing with the traditional sensors operating at transmission mode, the presented sensor in this work owns the advantages of smaller size and higher sensitivity and resolution due to the enhanced extinction ratio. The proposed structure is also promising for designing other tunable all-in-fiber photonic devices.

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References and links

1. H. Wang, S. Pu, N. Wang, S. Dong, and J. Huang, “Magnetic field sensing based on singlemode-multimode-singlemode fiber structures using magnetic fluids as cladding,” Opt. Lett. 38(19), 3765–3768 (2013).
2. S. Dong, S. Pu, and H. Wang, “Magnetic field sensing based on magnetic-fluid-clad fiber-optic structure with taper-like and lateral-offset fusion splicing,” Opt. Express 22(16), 19108–19116 (2014).
3. S. Brojabasi, B. Lahiri, and J. Philip, “External magnetic field dependent light transmission and scattered speckle pattern in a magnetically polarizable oil-in-water nanomulsion,” Physica B 454, 272–278 (2014).
4. S. Brojabasi, T. Muthukumaran, J. Laskar, and J. Philip, “The effect of suspended Fe3O4 nanoparticle size on magneto-optical properties of ferrofluids,” Opt. Commun. 336, 278–285 (2015).
5. S.-H. Xia, J. Wang, Z.-X. Lu, and F. Zhang, “Birefringence and magneto-optical properties in oleic acid coated Fe3O4 nanoparticles: application for optical switch,” Int. J. Nanosci. 10(03), 515–520 (2011).
6. S. Pu, X. Chen, L. Chen, W. Liao, Y. Chen, and Y. Xia, “Tunable magnetic fluid grating by applying a magnetic field,” Appl. Phys. Lett. 87(2), 021901 (2005).
7. R. Patel and R. V. Mehta, “Ferrodispersion: a promising candidate for an optical capacitor,” Appl. Opt. 50(31), G17–G22 (2011).
8. H. E. Horng, J. J. Chieh, Y. H. Chao, S. Y. Yang, C.-Y. Hong, and H. C. Yang, “Designing optical-fiber modulators by using magnetic fluids,” Opt. Lett. 30(5), 543–545 (2005).
9. S. Pu, S. Dong, and J. Huang, “Tunable slow light based on magnetic-fluid-infiltrated photonic crystal waveguides,” J. Opt. 16(4), 045102 (2014).
10. W. Lin, H. Zhang, B. Song, Y. Miao, B. Liu, D. Yan, and Y. Liu, “Magnetically controllable wavelength-division-multiplexing fiber coupler,” Opt. Express 23(9), 11123–11134 (2015).
11. T. Liu, X. Chen, Z. Di, J. Zhang, X. Li, and J. Chen, “Tunable magneto-optical wavelength filter of long-period fiber grating with magnetic fluids,” Appl. Phys. Lett. 91(12), 121116 (2007).
12. J. Dai, M. Yang, X. Li, H. Liu, and X. Tong, “Magnetic field sensor based on magnetic fluid clad etched fiber Bragg grating,” Opt. Fiber Technol. 17(3), 210–213 (2011).
13. Y. Chen, Q. Han, T. Liu, X. Lan, and H. Xiao, “Optical fiber magnetic field sensor based on single-mode-multiplexing single-mode structure and magnetic fluid,” Opt. Lett. 38(20), 3999–4001 (2013).
14. M. Deng, X. Sun, M. Han, and D. Li, “Compact magnetic-field sensor based on optical microfiber Michelson interferometer and Fe3O4 nanofluid,” Appl. Opt. 52(4), 734–741 (2013).
15. Y. Miao, J. Wu, W. Lin, K. Zhang, Y. Yuan, B. Song, H. Zhang, B. Liu, and J. Yao, “Magnetic field tunability of optical microfiber taper integrated with ferrofluid,” Opt. Express 21(24), 29914–29920 (2013).
16. P. Zu, C. C. Chan, G. W. Koh, W. S. Lew, Y. Jin, H. F. Liew, W. C. Wong, and X. Dong, “Enhancement of the sensitivity of magneto-optical fiber sensor by magnifying the birefringence of magnetic fluid film with Looy-Sagnac interferometer,” Sens. Actuators B Chem. 191, 19–23 (2014).
17. Y. Zheng, X. Dong, C. C. Chan, P. P. Shum, and H. Su, “Optical fiber magnetic field sensor based on magnetic fluid and microfiber mode interferometer,” Opt. Commun. 336, 5–8 (2015).
18. Y. Miao, H. Zhang, J. Lin, B. Song, K. Zhang, W. Lin, B. Liu, and J. Yao, “Simultaneous measurement of temperature and magnetic field based on a long period grating concatenated with multimode fiber,” Appl. Phys. Lett. 106(13), 132410 (2015).
19. T. Liu, Y. Chen, Q. Han, and X. Lu, “Magnetic field sensor based on U-bent single-mode fiber and magnetic fluid,” IEEE Photonics J. 6, 1–7 (2014).
20. P. Zu, C. C. Chan, W. S. Lew, L. Hu, Y. Jin, H. F. Liew, L. H. Chen, W. C. Wong, and X. Dong, “Temperature-insensitive magnetic field sensor based on nanoparticle magnetic fluid and photonic crystal fiber,” IEEE Photonics J. 4(2), 491–498 (2012).
21. A. Layeghi, H. Latifi, and O. Frazao, “Magnetic field sensor based on non-adiabatic tapered optical fiber with magnetic fluid,” IEEE Photonics Technol. Lett. 26(19), 1904–1907 (2014).
22. Z. Chen, V. K. Hsiao, X. Li, Z. Li, J. Yu, and J. Zhang, “Optically tunable microfiber-knot resonator,” Opt. Express 19(15), 14217–14222 (2011).
23. F. Xu, P. Horak, and G. Brambilla, “Optical microfiber coil resonator refractometric sensor,” Opt. Express 15(12), 7888–7893 (2007).
24. H. Luo, Q. Sun, Z. Xu, D. Liu, and L. Zhang, “Simultaneous measurement of refractive index and temperature using multimode microfiber-based dual Mach-Zehnder interferometer,” Opt. Lett. 39(13), 4049–4052 (2014).
25. M. Ding, P. Wang, and G. Brambilla, “A microfiber coupler tip thermometer,” Opt. Express 20(5), 5402–5408 (2012).
26. Y. Chen, S. C. Yan, X. Zheng, F. Xu, and Y. Q. Lu, “A miniature reflective micro-force sensor based on a microfiber coupler,” Opt. Express 22(3), 2443–2450 (2014).
27. W. B. Ji, H. H. Liu, S. C. Tjin, K. K. Chow, and A. Lim, “Ultrahigh sensitivity refractive index sensor based on optical microfiber,” IEEE Photonics Technol. Lett. 24(20), 1872–1874 (2012).
28. Y. Li, L. Chen, E. Harris, and X. Bao, “Double-pass in-line fiber taper Mach–Zehnder interferometer sensor,” IEEE Photonics Technol. Lett. 22(23), 1750–1752 (2010).
29. S. Lacroix, F. Gonthier, R. J. Black, and J. Bures, “Tapered-fiber interferometric wavelength response: The achromatic fringe,” Opt. Lett. 13(5), 395–397 (1988).
30. D. T. Cassidy, D. C. Johnson, and K. O. Hill, “Wavelength-dependent transmission of monomode optical fiber tapers,” Appl. Opt. 24(7), 945–950 (1985).

1. Introduction

Magnetic fluid (MF) is a kind of stable colloidal system consisting of surfactant-coated magnetic nanoparticles (usually 3-15 nm in diameter) dispersed in a suitable liquid carrier [1]. It possesses both the features of magnetic property of solid magnetic materials and fluidity of liquids. MF presents versatile magneto-optical properties including Faraday effect, tunable refractive index (RI), field dependent transmission and birefringence, magnetochromatics and nonlinear optical effect [2–4]. Thus, many unique optical devices based on MF have been designed, such as optical switches [5], optical gratings [6], tunable optical capacitors [7], modulators [8], tunable slow light [9], wavelength-division multiplexing [10], and magnetic field sensors employing various fiber structures (e.g. fiber grating [11, 12], fiber-based interferometer [13–19], and photonic crystal fiber (PCF) [20]). Comparing with the traditional devices, the MF-based corresponding optical devices possess the advantages of high sensitivity and small size [21].

Recently, many optical devices based on microfiber are springing up, such as microfiber knot resonator [22], microfiber coil resonator [23], microfiber refractometer [24], thermometer [25] and micro-force sensor [26]. These are assigned to the unique geometry of microfiber, which possesses the characteristic of low dimension, large evanescent field, strong light confinement, low loss and robustness [27]. The outstanding properties make microfiber-based photonic devices promising for designing novel sensors with high sensitivity, compact size, low cost and fast response.

Considering these, the combination of microfiber with MF may provide a prospective approach for magnetic field measurement. In this work, a reflective all-fiber magnetic field sensor based on a MF-clad non-adiabatically tapered microfiber (NATMF) is proposed and experimentally demonstrated. Owing to the large evanescent field outside the NATMF surface, the transmission properties of the NATMF is extremely sensitive to the surrounding RI. Hence, the reflection spectrum of the proposed structure will vary with the magnetic field.
due to the unique feature of magnetic-field-dependent RI of MF. By monitoring the dip wavelength change in the reflection spectrum, the magnetic field strength can be interrogated. Comparing with other transmission-type magnetic field sensors, the input and output fibers of reflective microfiber sensor can be easily combined together. Consequently, reflective microfiber sensor is compact and has the potentials of being easily utilized in some harsh condition, such as narrow gap, long-distance measurement. In addition, as the extinction ratio of received power is larger in reflection spectrum (so-called double-pass spectrum) than in transmission spectrum [28], the accuracy of interrogating the interference dip wavelength will be improved when monitoring reflection spectrum. This will increase the sensing performance.

2. Experimental details

As the wavelength response of adiabatic tapered microfiber sensor is insensitive to environment fluctuation [27], NATMF with abruptly tapers and much smaller waist diameter is fabricated for highly sensitive magnetic field sensor in this work. A NATMF is manufactured by a fusion splicer combining with the additional flame brushing method. We called this technique two-step method. Two abrupt tapers on a piece of single mode fiber are firstly made with the fusion splicer. Then, employing the additional flame brushing method, a long uniform waist is achieved between the abrupt tapers. Figure 1 shows the microscope image of the as-fabricated NATMF in this work. The NATMF with length of 2.5 mm and waist diameter of 3.88 μm is fabricated with a piece of sing-mode fiber. Two abrupt transitions at the ends of the tapering region are clearly observed.

![Microscope image of NATMF](image)

Figure 1. (a) Microscope image of NATMF and (b) NATMF waist.

Figure 2 shows the schematic configuration of the proposed sensor. It is fabricated by immersing a NATMF into MF and then sealed in a capillary tube. Both ends of the capillary are sealed with UV glue to avoid MF leaking or evaporating. To make the sensor work in the reflection mode, a fiber mirror was connected to one end of the SMF. In our experiments, the water-based MF provided by Beijing Sunrise Ferrofluid Technological Co., Ltd. is employed. The particle density and saturation magnetization of the MF are 1.18 g/cm³ (25 °C) and 200 Oe, respectively. The average diameter of the magnetic nanoparticles is around 10 nm. The MF is diluted with distilled water. The volume ratio of water-based MF to distilled water is 1:10. The RI of the diluted MF is estimated to be around 1.34 at zero magnetic field.
The experimental measurement setup is shown in Fig. 3. The sensing structure is placed between two poles of an electromagnet, which generates a uniform magnetic field with nonuniformity of less than 0.1% within the sample region. The strength of magnetic field is adjusted by tuning the magnitude of the supply current. The magnetic field direction is perpendicular to the optical fiber axis. A Tesla meter is used to measure the strength of the magnetic field. Light from a supercontinuum broadband source (SBS, Wuhan Yangtze Soton Laser Co., Ltd.) is launched into the NATMF through a Y-coupler. The reflected light from the sensor head is collected by an optical spectrum analyzer (AQ6370C). During our experiments, the ambient temperature is kept at 18 °C.

3. Results and discussion

Figure 4 shows the reflection spectra of the NATMF before and after being immersed into MF without external magnetic field. Herein and hereafter, the wavelength range covering the fiber communication windows is specifically selected for investigating in details. Because of the fractional mode power extending outside the microfiber and the absorptive properties of MF, a distinct decrease in transmission can be observed in the spectrum. It can also be observed that the dip wavelength spacing becomes bigger when NATMF is immersed into MF. For both cases, the dip wavelength spacing increases slightly as the incident wavelength goes long.
To investigate the magnetic field sensing properties of the as-fabricated structure, the reflection spectra at different magnetic field strengths are experimentally measured and shown in Fig. 5. Figure 5 indicates that the interference dip wavelength red-shifts with the magnetic field and the corresponding peak intensity decreases with magnetic field. The dip wavelength spacing increases slightly with magnetic field and becomes a little larger at long wavelength side for certain magnetic field case.

For a nonadiabatic biconical fiber taper, part of light energy of the fundamental $HE_{11}$ mode at the untapered region will be coupled into the cladding $HE_{in}$ modes at the tapered region. Besides, Lacroix et al. have pointed out that an abruptly tapered fiber can be considered as a modal interferometer with the same characteristic properties as a two-mode fiber (an untapered few-mode fiber) [29]. As a result, the transmission spectrum contributed to the interference between $HE_{11}$ and $HE_{in}$ modes can be expressed as [29]

$$I_i = I_1 + I_2 + 2\sqrt{I_1I_2} \cos \phi,$$

(1)
where $I_m$ ($m = 1, 2$) is the power coupling between the fundamental $HE_{11}$ and cladding $HE_{1m}$ modes, $\phi$ is the phase difference between $HE_{11}$ and $HE_{1m}$ modes. Considering a uniform tapered region, $\phi = \Delta \beta L$, where $L$ is the length of the tapered region, $\Delta \beta$ is the propagation constant difference between the two involved modes, which can be expressed as [30]

$$
\Delta \beta = \frac{\lambda}{4\pi n_r r^2} \exp \left( -\frac{2}{V} \right),
$$

where $V = \frac{2\pi}{\lambda} \sqrt{n_i^2 - n_0^2}$ represents the normalized frequency, $n_i$ is the RI of fiber cladding, $n_0$ is the RI of external medium, $\lambda$ is the light wavelength in vacuum, $r$ is the radius of the taper waist, $U_1^\infty$ and $U_2^\infty$ are the asymptotic values of $U$ parameters for the two involved coupling modes. So, the reflection spectrum of the proposed system is given by $I_m = RI_m$, where $R$ is the mirror reflectivity.

Usually, the coupling occurs preferentially between the $HE_{11}$ and $HE_{12}$ modes since both modes have similar azimuthal symmetry and the phase mismatch for this two modes is minimized [30]. In addition, the relatively regular variation in reflection spectra shown in Figs. 4 and 5 implies the low-order mode propagation within the NATMF [30]. In order to determine the number and power distribution of the modes, the fast Fourier transform (FFT) method is used to obtain the spatial frequency spectrum of the interference pattern shown in Fig. 5. The corresponding result is depicted in Fig. 6. Figure 6 indicates that the power is primarily distributed in the fundamental core mode and first-order cladding mode. The other excited cladding modes are very weak. This confirms the aforementioned prediction that the observed interference spectra are assigned to the coupling between the core $HE_{11}$ and cladding $HE_{12}$ modes. Therefore, the values of $U$ parameters in Eq. (2) are equal to $U_1^\infty (HE_{11}) = 2.405$ and $U_2^\infty (HE_{12}) = 5.520$. Neglecting the material dispersion, Eqs. (1) and (2) imply that the guided reflection spectrum is approximately a sinusoidal function of the wavelength, which agrees well with the experimental measurements (see Figs. 4 and 5).

![Fig. 6. Spatial frequency spectrum of the interference patterns shown in Fig. 5.](image)

The dip wavelength spacing, i.e. free spectral range (FSR) as a function of wavelength $\lambda$ and environmental RI $n_0$ is derived as [29]
According to Eq. (3), the FSR will increase with the environmental RI $n_0$ and the incident wavelength $\lambda_0$. As the RI of MF increases with magnetic field and is always larger than that of air, the FSR for the NATMF immersed in MF will be larger than that immersed in air and increases with magnetic field strength as well. This well explains the observed experimental results shown in Figs. 4 and 5. Simultaneously, the wavelength-dependent FSR observed in Figs. 4 and 5 is apparent according to Eq. (3).

Figure 5 shows that the interference dip wavelength and transmission loss change gradually with magnetic field. Seven typical dip wavelengths are selected to investigate the magnetic field sensing properties of the as-fabricated MF-clad NATMF. The dip wavelength shift with magnetic field is replotted in Fig. 7. Figure 7 reveals that all of the dip wavelengths shift towards longer wavelength as magnetic field strength increases, but exhibit a nonlinear behavior, which is due to the Langevin-like function relationship between the RI of MF and magnetic field [15]. The magnetic-field-induced RI variation of MF is assigned to the agglomeration of magnetic nanoparticles within MF under external magnetic field. As the external magnetic field is applied, agglomeration of nanoparticles happens and then the phase separation occurs. This will result in the increase of MF’s RI with magnetic field. When the external magnetic field is sufficiently high, almost all of the nanoparticles are agglomerated to form the magnetic columns, so the RI of MF will changes very slightly with magnetic field further increase.

At relatively low magnetic field (0-100 Oe), the dip wavelength variation with magnetic field is slight and unobvious. At relatively high field regime (beyond 225 Oe), the response of dip wavelength to magnetic field tends to lower and finally saturate. When the magnetic field strength lies between 100 and 225 Oe, the response shows good linearity and linear fitting ($R^2$ values exceed 0.99) is applied to the experimental data. The sensitivities of 86.7 pm/Oe, 98.2 pm/Oe, 107.1 pm/Oe, 119.5 pm/Oe, 140 pm/Oe, 162.5 pm/Oe and 174.4 pm/Oe are achieved for dip wavelength around 1227 nm, 1267 nm, 1309 nm, 1354 nm, 1400 nm, 1453 nm and 1511 nm, respectively. The obtained sensitivity of the proposed sensing structure is twice larger than that of the structure based on multimode interference (90.5 pm/Oe) [13], ~10 times larger than that of long period grating-based structure (~18.3 pm/Oe) [11], and ~73 times higher than that of MF-coated PCF structure (~2.4 pm/Oe) [20]. Thanks to the smaller taper diameter, the sensitivity of the reflective sensor in this work is about ~24 times higher than...
that of transmission-type sensor using a similar nonadiabatic tapered optical fiber structure (~7.2 pm/Oe) [21]. For the 0.02 nm wavelength resolution of OSA, the achieved resolution of magnetic field sensing are about 0.231 Oe, 0.204 Oe, 0.187 Oe, 0.167 Oe, 0.143 Oe, 0.123 Oe, 0.115 Oe when monitoring different dip wavelengths. Finally, we would like to point out that another similar magnetic field sensing scheme has been recently proposed, which is based on taper-like and lateral-offset fusion splicing techniques [2]. But the work in [2] is based on the cladding-mode interference due to the relatively large lateral-offset. It operates at transmission mode and the sensing area is relatively long (19 mm) [2]. On the contrary, the sensing structure proposed in this work is much compact (2.5 mm length for the sensing area) and operates at refection mode, which can be easily adopted. Moreover, the sensitivity achieved in this work (174.4 pm/Oe or higher) is much higher than that in [2] (26 pm/Oe). This may be assigned to the different physical mechanism (core-cladding mode interference) and thinner microfiber employed in this work.

Figure 7 also implies that the sensitivity of wavelength shift is wavelength dependent. The sensitivity as a function of dip wavelength is explicitly plotted in Fig. 8. Figure 8 displays that the sensitivities increase with dip wavelength and the dependence of sensitivity on dip wavelength is almost linear. Therefore, the linear fitting is applied. The slope of 0.3237 (pm/Oe)/nm with $R^2$ value of 0.9849 is achieved.

![Fig. 8. Sensitivity as a function of dip wavelength.](image)

From Eqs. (1) and (2), the wavelength shift due to the change of external RI $n_0$ can be derived as

$$\frac{d\lambda}{dn_0} = -\frac{\partial\phi}{\partial\lambda} \frac{1}{\partial\phi / \partial n_0} = \frac{2\lambda n_0}{(V-2)(n_1^2-n_0^2)}.$$  \hspace{1cm} (4)

As the proposed structure is operating at the condition far from cutoff, the fiber parameter $V > 2.405$. Therefore, $d\lambda/dn_0 > 0$ according to Eq. (4). So, Eq. (4) implies that $d\lambda/dn_0$ will increase with $\lambda$ and/or $n_0$ increase and $r$ decrease. This agrees with the experimental results shown in Fig. 8 very well. Hence, operating at long wavelength is an alternative means to enhance the sensing sensitivity of the proposed structure. The aforementioned experimental results and theoretical analysis indicate that the sensitivity and resolution of the proposed NATMF sensor can be further enhanced by increasing the MF concentration, optimizing the RI of MF, decreasing the taper diameter and increasing the taper length. However, decreasing the taper diameter is limited by the propagating loss induced by light scattering on the surface of the taper waist. Thus, optimizing taper diameter is required [30].
In addition to the dip wavelength shift, the contrast ratio of the interference fringes decreases gradually with magnetic field as shown in Fig. 5, which is assigned to the magnetic-field-dependent evanescent field absorption of MF. The contrast ratio defined in [28] is employed, which is given as

\[
P = 10 \cdot \log_{10} \left[ \left( \sqrt{I_1} + \sqrt{I_2} \right) / \left( \sqrt{I_1} - \sqrt{I_2} \right) \right]^2.
\]  
(5)

It is well-known that the attenuation coefficient \( \alpha \) of MF increases with magnetic field, which will result the intensity decrease of fundamental and cladding modes as shown in Fig. 6. As the cladding mode has much larger evanescent than that of fundamental mode, the attenuation coefficient for cladding mode is bigger than that for fundamental mode. This will lead to contrast ratio \( P \) decrease with magnetic field according to Eq. (5), which can be clearly seen in Fig. 5. This phenomenon also implies a possibility of intensity-based magnetic field sensor. To quantitatively assess the variation of contrast ratio, the fringe visibility is defined as \( V_f = \left( T_{\text{peakL}} + T_{\text{peakR}} \right) / 2 - T_{\text{dip}}, \) where \( T_{\text{dip}}, T_{\text{peakL}}, \) and \( T_{\text{peakR}} \) are reflection powers at certain dip wavelength, the adjacent left and right peaks of the selected dip, respectively. The dip wavelength at around 1309 nm with an initial \( V_f \) of 14 dB is considered as an example. The variation of \( V_f \) with magnetic field is shown in Fig. 9. The response of \( V_f \) to \( H \) is generally nonlinear, which is similar to the dip wavelength shift with magnetic field (see Fig. 7). This may be due to the same physical process dominating the wavelength shift and transmission loss, viz. magnetic nanoparticle agglomeration. When the magnetic field strength lies between 75 and 225 Oe, a fair linear relationship is obtained. The corresponding sensitivity is obtained to be 0.02 dB/Oe with \( R^2 \) value of 0.98.

4. Conclusion

In conclusion, a kind of magnetic field sensor based on MF-clad NATMF is proposed and experimentally demonstrated. Though the MF concentration is low, a relatively high magnetic field sensing sensitivity is obtained. The highest sensitivity of 191.8 pm/Oe can be obtained at around 1537 nm. Besides, the sensitivity of the wavelength shift is wavelength-dependent and the corresponding sensitivity of 0.3237 (pm/Oe)/nm is achieved. The sensitivity of fringe visibility variation with respect to magnetic field is \(-0.02 \) dB/Oe. It is worth noticing that the sensitivity of the proposed MF-clad NATMF sensor can be further enhanced by optimizing the RI of MF and taper parameter. Considering the compact size, low cost, large extinction...
ratio and high sensitivity of the proposed structure, it is promising for other tunable all-in-fiber photonic devices.

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