An Optical Microfiber Taper Magnetic Field Sensor With Temperature Compensation

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***Abstract*— We proposed an optical magnetic field sensor with the temperature correction capability, which is based on an optical microfiber taper (OMT) integrated with magnetic fluid. The OMT is fabricated simply by fused tapering and then sealed into a capillary tube filled with magnetic fluid. The sensor is highly sensitive to magnetic field with the sensitivity of 0.171 nm/Oe in the range of 20–70 Oe at room temperature 25 °C. Moreover, there is a linear relationship between the wavelength shift and temperature in the range of 30 °C–80 °C, and a sensitivity of −0.587 nm/°C has been achieved. Based on these experiments, we provided a sensitivity matrix to correct the errors caused by temperature in order to measure magnetic field more accurately.**

***Index Terms*— Fiber optic sensors, fiber tapers, magnetic fluid, magnetic field sensors.**

I. INTRODUCTION

OPTICAL fiber sensors have been extensively researched and applied in physical and chemical sensing field, such as strain, temperature, refractive index and solution concentrations [1]–[7], due to their advantages of small size, fast response, remote monitoring and corrosion resistance. In recent years, magnetic field sensors based on optical fiber devices were developed [8]–[14]. For example, Liu achieved a tunable magneto-optical wavelength filter of long-period fiber grating with magnetic fluids [8]; Peng implemented magneto-optical fiber sensor configured as Sagnac interferometer structure [9]; Li proposed an all-fiber magnetic-field sensor based on microfiber knot resonator and magnetic fluid [10]; Miao and Layeghi proposed tunable magnetic field sensors based on taper and magnetic fluid [11], [12]; Optical magnetic field sensor based on ferrofluid-infiltrated microstructured optical fiber long-period grating [12] or fluid-filled photonic crystal fibers [13] also have been developed. However, the sensitivity of these sensors [8]–[11] only can reach tens pm/Oe order of magnitude or even smaller. Although the sensitivity of these sensors [13], [14] increased, they could not be widely used due to their complex construction. Besides, the temperature has a great influence on the magnetic field measurement due to the refractive index of magnetic fluid can be changed with different temperature [18], [19], so the temperature must be considered in optical fiber sensor integrated with magnetic fluid.

In this paper, we demonstrate a simple, cost-effective and ultrasensitive optical magnetic field sensor with the temperature correction capability, which is based on an optical microfiber taper integrated with magnetic fluid. The sensor has high sensitivity to magnetic field due to OMT with small diameter and large proportion of evanescent field energy. Besides, the temperature factor is also taken into account in the magnetic field measurement.

II. FABRICATION

The magnetic field experimental setup of the OMT for sensing measurement is illustrated in Fig. 1(a). It includes a supercontinuum broadband light source (BBS) (Superk Compact, NKT Photonics, Inc.), an optical spectrum analyzer (OSA) (AQ6370B, Yokogawa) to record the transmission spectrum change, a sensor probe, two electromagnets to generate the magnetic field and a tunable voltage source (TVS) to tune the intensity of the external magnetic field. In order to measure the magnetic field intensity, a Tesla meter (TM) with a resolution of 0.1Oe is placed perpendicularly to the external magnetic field. The magnetic fluid used in this experiment is EMG605 (Ferrotec, Japan). Its average particle size is smaller than 10 nm and refractive index (RI) changes with the external magnetic field and temperature. The volume concentration and saturation magnetization of the magnetic fluid are 3.6% and 200 Oe, respectively. When no magnetic field is applied, RI of magnetic fluid EMG605 is estimated to be around 1.40. Before it comes into use, it needs to be diluted with deionized water in proportion of 1:1.7, because the RI of magnetic fluid is higher than the detection limit of OMT.

The OMT in the sensor probe was fabricated on common telecom single-mode optical fiber (SMF-28e, Corning, Inc.) in the fusion splicer (Ericsson FSU-975) with additional tension on one side. The fabricated OMT was inserted into a capillary tube with the length and inner diameter of 2 cm and 300 μm,

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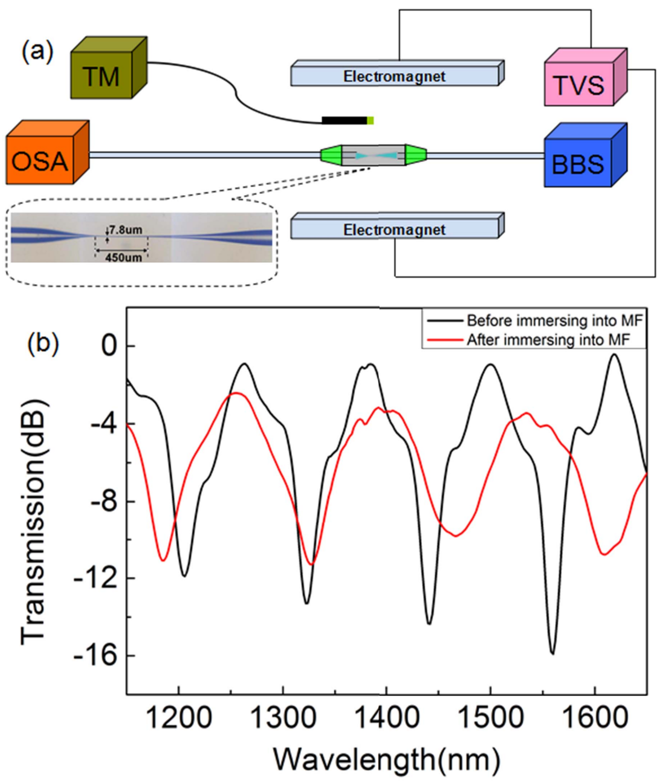

Fig. 1. (a) Experimental setup for the magnetic field sensing. The inset shows optical microscope image of the OMT. (b) Transmission spectra of the OMT before and after immersing in the ferrofluid.

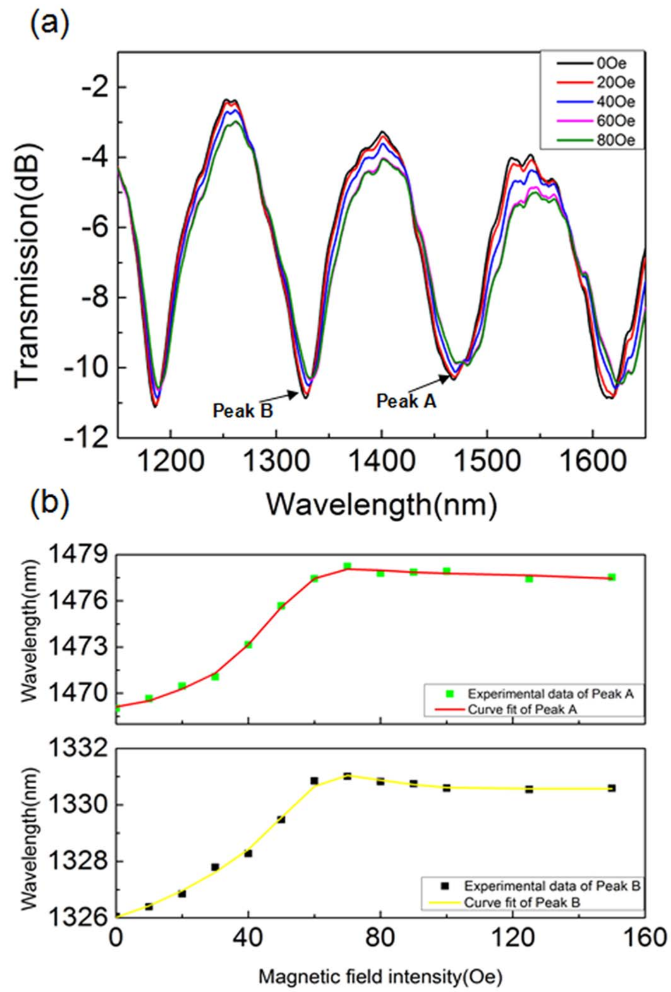

Fig. 2. (a) Transmission spectra of the magnetic fluid-sealed OMT under different magnetic fields intensity. (b) Relationships between magnetic fields intensity and wavelength shift of the resonant peaks.

respectively. After the capillary tube was filled with magnetic fluid by capillary force, the two ends of the capillary tube were sealed with AB glue immediately. The inset of Fig. 1(a) shows the optical microscope image of OMT, its waist diameter and length are 7.8 μm and 450 μm, respectively. The transmission spectrum of this OMT before and after immersing in the magnetic fluid is shown in Fig. 1(b) with the insertion loss of 2 dB. When the light propagates into the OMT, a part of energy in the fundamental mode will couple into high-order modes due to the perturbation. The size of the waist diameter plays an important part in power distribution in the modes. If the waist diameter is larger than 10 μm (but smaller than 30 μm), multimode interference will appears [15], which will impact the stabilization of the wavelength shift when the temperature or magnetic field changes. Besides, the sensitivity with smaller diameter can be enhanced due to the stronger evanescent-field interaction [21]. On the other hand, the waist diameter could not be too small. With smaller waist diameter, the OMT achromatic fringe in the transmission spectrum will be "cut off" under high magnetic field [16]. As a result, the detection limit of the OMT will become smaller and magnetic fluid with lower concentration has to be used, which means magnetic fluid will be easier to be saturated under the weak magnetic field and detectable range will be narrower.

III. Experiment Result and Discussion

In our previous research, we have found that the OMT is very sensitive to the refractive index and the sensitivity is as high as 18989 nm/RI [7]. The refractive index of magnetic fluid can be tuned by magnetic field and temperature [18], [19], sensing experiments have been carried out to test the response to magnetic field and temperature. Magnetic field experiment was conducted at room temperature (25 °C). Fig. 2(a) shows the transmission spectra change with the magnetic field strength. With the increase of magnetic field intensity, the transmission spectrum has a significant red shift until the magnetic field intensity increase to a saturated value of 80 Oe. The relationships between magnetic field intensity and wavelength shift of different loss peaks are shown in Fig. 2(b). It could be found two sensitive and linear regions according to the peak shift for different applied magnetic field intensities. When the magnetic field increases to 80 Oe, loss peaks will no longer move due to the magnetic fluid becomes saturated magnetization. The curves of peak A and peak B in Fig. 2(b) conform to Langevin curve [19]. From magnetic field intensity 20 Oe to 70 Oe, the sensitivity of the peak A and B are 0.171 nm/Oe and 0.084 nm/Oe, respectively.

The magnetic fluid used in this experiment is water-based, hence thermo-optic coefficient of the magnetic fluid is estimated to be -0.8×10^{-4}/°C, which is little different with thermo-optic coefficient of water. As the temperature increases, the RI of the magnetic fluid decreases rapidly

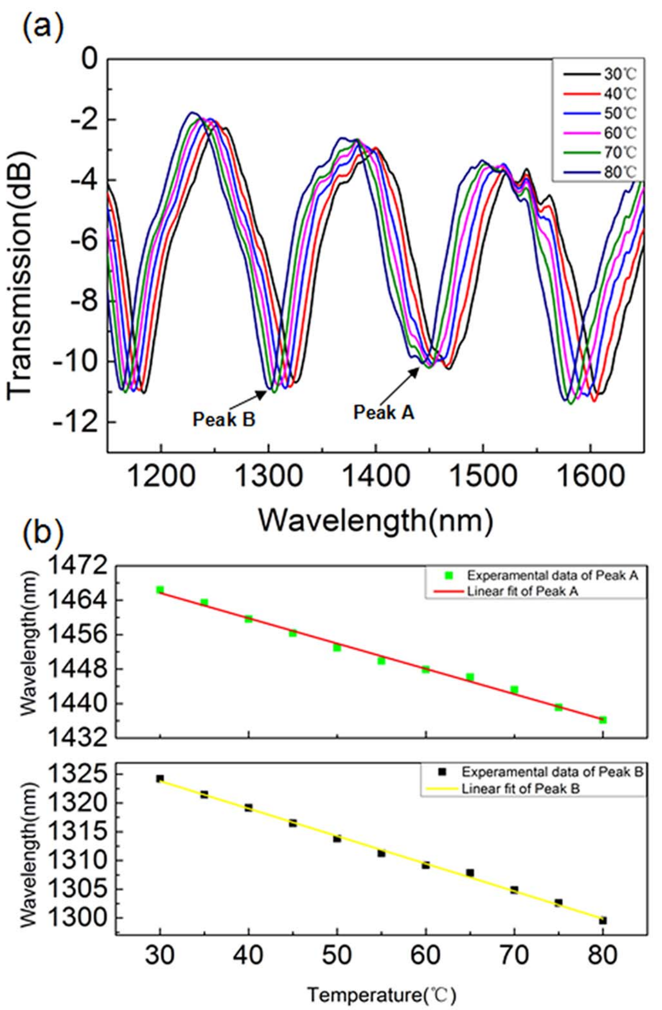

Fig. 3. (a) Transmission spectra of the magnetic fluid-sealed OMT under different temperatures. (b) Relationships between temperature and wavelength shift of the resonant peaks.

and significant blue shifts of transmission spectrum were observed, as shown in Fig. 3(a). The temperature test is carried out in an oil bath with the resolution of 0.01 °C, where sensor probe could be completely immersed into oil. As shown in Fig. 3(b), in the range of 30 °C to 80 °C, the relationships between temperature and wavelength shift of these resonant peaks are linear, which shows a sensitivity of −0.587 nm/°C and −0.479 nm/°C, respectively. From the experiment result, it seems the temperature has a great influence on the magnetic field measurement.

In order to measure the magnetic field under different temperature more accurately, we provided a sensitivity matrix to correct of errors caused by temperature,

$$\begin{bmatrix} \Delta M \\ \Delta T \end{bmatrix} = \frac{1}{k_{TA} \cdot k_{MB} - k_{MA} \cdot k_{TB}} \begin{bmatrix} -k_{TB} & k_{TA} \\ k_{MB} & -k_{MA} \end{bmatrix} \begin{bmatrix} \Delta\lambda_A \\ \Delta\lambda_B \end{bmatrix}$$

where ΔM is the variation of the magnetic field intensity, ΔT is the variation of the temperature, $\Delta\lambda_A$ and $\Delta\lambda_B$ are the wavelength shifts of peak A and B, k_{MA} and k_{TA} are the magnetic field intensity and temperature coefficient for $\Delta\lambda_A$, respectively. k_{MB} and k_{TB} are the magnetic field intensity and temperature coefficient for $\Delta\lambda_B$, respectively. The magnetic field and temperature coefficients k_M and k_T have been obtained earlier in the paper, respectively. The equation can be written as follows,

$$\begin{bmatrix} \Delta M \\ \Delta T \end{bmatrix} = \frac{1}{0.024} \begin{bmatrix} 0.479 & -0.587 \\ 0.084 & -0.171 \end{bmatrix} \begin{bmatrix} \Delta\lambda_A \\ \Delta\lambda_B \end{bmatrix}$$

Simultaneous sensing of the magnetic field intensity and temperature is enabled through the measurement of the wavelength shift of peak A and B. This also means that it can be more accurate to measure the magnetic field and to eliminate the errors caused by temperature. In order to assess the performance of the sensor, we use the condition number of the matrix to estimate the sensitivity of matrix operation to error in measurement [20]. Here we get the reciprocal of the condition number rcond(K) = 0.0288 of the above matrix, which is larger than [20]. Hence the matrix is well conditioned and this method is feasible.

IV. Conclusion

In conclusion, we have proposed an optical magnetic field sensor with the temperature correction capability, which is based on an optical microfiber taper integrated with magnetic fluid. The OMT is fabricated simply by fused tapering and then sealed into capillary tube filled with magnetic fluid. We got a sensitivity of 0.171 nm/Oe and 0.084 nm/Oe in the magnetic field intensity range of 20Oe to 70Oe at room temperature 25 °C. Moreover, sensitivities to temperature are −0.479 nm/°C and −0.587 nm/°C in range of 30-80 °C. In order to measure magnetic field more accurately in different temperature, we provided a sensitivity matrix to correct of errors caused by temperature. It is expected that the sensor can be widely applied in tunable photonic devices, especially under the condition of temperature instability.

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