Differential twin receiving fiber-optic magnetic field and electric current sensor utilizing a microfiber coupler

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Abstract: A magnetic field and electric current meter is proposed based on a differential twin receiving microfiber coupler (MC) sensor. The sensor is fabricated by bonding a MC and an aluminium (Al) wire together. With the small diameter of several micrometers, the output power at each port of the coupler shows high sensitivity to the distortion of Al wire from the Lorentz force induced by the magnetic field or the thermal expansion caused by the electric current. The ratio of the difference to the sum of the output signals from the two output ports can be used to eliminate the variation in the sensitivity. Using our proposed sensor, we measured a magnetic field sensitivity of ~0.0496 mT^{-1}, current sensitivity of ~1.0899 A^{-1} without any magnetic field, and good repeatability are also shown in this paper.

OCIS codes: (060.1810) Buffers, couplers, routers, switches, and multiplexers; (060.2370) Fiber optics sensors; (060.2340) Fiber optics components.

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1. Introduction

Over the last three decades, optical fiber sensor technology has been widely studied and developed. Compared with traditional sensors, optical fiber sensors have several superior performances such as their insensitivity to electromagnetic interference, electrical isolation, light weight, high sensitivity, and ease to connect to other fiber devices [1]. Electric current sensors and magnetic field sensors are typical applications of fiber-optic sensors. Fiber-optic based electric current sensors are mainly divided into two categories based on Faraday effect and thermal effect [2, 3]. Magnetic field sensors have been developed based on magnetic fluid [4–6], magnetic force [7], magnetostrictive effect [8], Faraday effect [9] and Ampere force [10, 11], etc. Diverse optical fiber devices based on grating, interferometer, resonator and laser have been demonstrated to measure magnetic or electrical field [12, 13]. Recently, as the quick development of microfiber technique, a lot of research efforts have been devoted to microfiber based magnetic field or electric current sensors with more compact size and higher sensitivity. Most of these works are based on microfiber resonators and wavelength-dependent, for example, electrical-field sensor based on Faraday effect or thermal-optic effect in a microfiber coil resonator, magnetic-field sensor based on microfiber knot resonator and magnetic fluid [14]. However, the fabricating and packaging of resonators are still challenging and the magnetic fluid has the disadvantages of intrinsic magnetic hysteresis and saturation effect.

In the meantime, increasing interest has been paid to the simplest microfiber device — coupler and its applications in sensing and signal processing, for example, high-temperature sensor [15], mode filter [16], spatial mode conversion [17]. Thanks to the peculiarity of a microfiber coupler (MC) such as the subwavelength-diameter waist and unique geometry with multiple input-output ports, it is more sensitive to the force than ordinary fiber devices and offers convenient multiplexing capabilities. Besides, a MC is easier to be manufactured, compared with other microfiber devices such as a resonator and a grating. In this work, a new kind of differential twin receiving fiber sensor taking these advantages of a MC is presented. The sensor is configured by bonding a MC to an aluminium (Al) wire, and can measure both the magnetic field and electric current based on Lorentz force or thermal expansion of the Al wire, respectively. The sensor is simple, low-cost, and has no intrinsic magnetic hysteresis and saturation effect including no magnetic material. Seen from the movement of the wavelength spectrum, the magnetic field sensitivity can reach 51.3 pm/mT when 80mA electric current is applied, higher than that reported before [11]. The sensor utilizes the ratio of the difference to the sum of the twin-output power. This approach eliminates the dependence on the perturbation of incident light power and doesn't need an expensive optical spectrum analyzer. Using our proposed sensor, we measured a magnetic field sensitivity of ~0.0496 mT^{-1}, and a current sensitivity of ~1.0899 A^{-1} without any magnetic field.

2. Fabrication and principle

To fabricate the sensor, we use two commercial single-mode fibers (SMF-28, Corning, USA) to fabricate a MC with the so-called flame brushing method [18]. Initially, the polymer coating layer is stripped and the two fibers are placed without any twist side by side fixed on the stages. Then, a hydrogen-oxygen flame is used to heat and the fibers are tapered to a MC. The MC includes a uniform waist region, two transition regions, and four I/O ports as seen from the inset of Fig. 1. Light injects into Port 1 or Port 2, and exits from the twin-output Port 3 and Port 4.

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For simplification, the MC can be treated as a weakly fused coupler [19], approximately as two touching cylindrical waveguides side by side. Supposing light injects into Port 1, the normalized power at the twin-output Port 3 and Port 4 can be described by:

$$P_3 = \frac{1}{2} I_0 \left\{1 + \cos\left[\left(\tilde{C}_x + \tilde{C}_y\right)L\right] \cdot \cos\left[\left(\tilde{C}_x - \tilde{C}_y\right)L\right]\right\}, \tag{1}$$

$$P_4 = \frac{1}{2} I_0 \left\{1 - \cos\left[\left(\tilde{C}_x + \tilde{C}_y\right)L\right] \cdot \cos\left[\left(\tilde{C}_x - \tilde{C}_y\right)L\right]\right\}. \tag{2}$$

where I_0 is the power of light injecting into Port 1, L is the coupling length, $\tilde{C}_x$ and $\tilde{C}_y$ are coupling coefficients for x and y polarizations averaged over the whole coupling region, respectively. We deal with the experiment data in differential data processing as follows:

$$\frac{P_3 - P_4}{P_3 + P_4} = \cos\left[\left(\tilde{C}_x + \tilde{C}_y\right)L\right] \cdot \cos\left[\left(\tilde{C}_x - \tilde{C}_y\right)L\right]. \tag{3}$$

Then, we define Γ as the ratio of the difference to the sum of the output signals from the twin-output ports:

$$\Gamma = \frac{P_3 - P_4}{P_3 + P_4}. \tag{4}$$

which shows that Γ is independent on the input power. Moreover, the MC is thin and changes of coupling coefficients and coupling length are very small in our experiment, Γ is approximately assumed to be linear with L or the distortion of the Al wire.

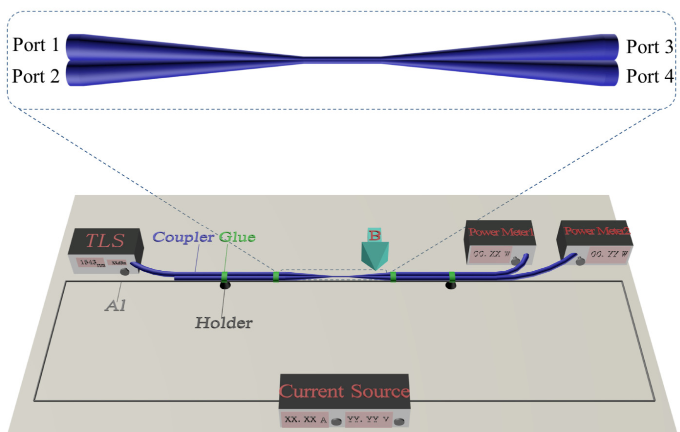

Fig. 1. The schematic diagram of the differential twin receiving fiber-optic magnetic field and electric current sensor. The electric current flows through the Al wire, and the applied magnetic field is perpendicular to the current. The inset shows the schematic diagram of the MC.

Figure 1 shows the schematic diagram of the entire differential twin receiving fiber-optic magnetic field and electric current sensor. The tunable laser source (TLS) (8163B, Agilent) and two power meters (S145C, Thorlabs) are used to recognize the tiny change of the MC on account of the distortion of the Al wire throughout the entire experiment. In Fig. 1, the blue wire represents the MC and the grey straight line represents the Al wire. The MC and the Al wire are almost collinear. The green rectangles represent the glue used to bond the Al wire and the MC together and fix all their ends on the holders. The current source (N5747A, Agilent) provides an electric current to flow through the Al wire, and the experiment device is

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kept under a stable perpendicular magnetic field adjusted by a magnetic field controller (MB-2A, NJUWH).

The Al wire with a certain electric current in a perpendicular magnetic field subjects to the effect of Lorentz force, which is:

$$F_{Lorentz} = B \cdot I \cdot L_{Lorentz}. \tag{5}$$

where F_{Lorentz} is the Lorentz force, B is the perpendicular magnetic flux density, I is the electric current, and L_{Lorentz} is the length of the Al wire under the magnetic field. Because of the existence of the Lorentz force, the Al wire distorts slightly. Component of the Lorentz force acts longitudinally on the MC which causes small changes in the refractive index and coupling length. The changes can be predicted by formulas expressed below:

$$\frac{\Delta L}{L} = \frac{f}{EA}. \tag{6}$$

$$\frac{\Delta n_1}{n_1} = -\frac{f}{EA} \cdot P. \tag{7}$$

where n_1 and E are the refractive index and the Young's modulus of the microfiber. A is the area of coupling region cross section. P is the effective photo-elastic coefficient. f is the force acting longitudinally on the MC.

Besides, with no magnetic field, heat is generated by electric current which is linearly with the square of the current, leads in thermal expansion effect. It can distort the Al wire, and result in the similar influences as the Lorentz force.

We define the sensitivity S of the sensor through the change of Γ in Eq. (4) per magnitude of electric current or magnetic field, which can be expressed by:

$$S_B = \frac{\partial \Gamma}{\partial B}, S_I = \frac{\partial \Gamma}{\partial I}. \tag{8}$$

Such a new kind of unit of sensitivity is different with conventional wavelength-shift sensitivity. We propose it because of the specific situation and unique property of the MC. Due to the property of twin-output ports, this approach eliminates the dependence on the perturbation of incident light power and doesn't need an expensive optical spectrum analyzer.

Figure 2 shows the calculated longitudinal force sensitivity with different microfiber diameter. As we can see, the thinner the microfiber is, the more sensitive it is to the external force. When the Lorentz force is applied, the Al wire will be slightly bent and the longitudinal force will induce the variances of both the coupling length and the refractive index. According to our calculation, the variances of both the coupling length and the refractive index cause analogous effect on the power change, and both of them should be considered.

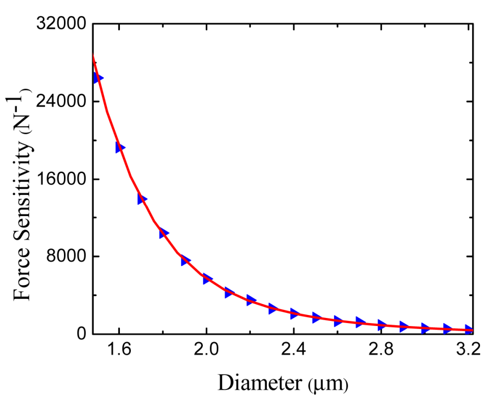

Fig. 2. The calculated longitudinal force sensitivity with different microfiber diameter.

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3. Experiment results

Figure 3(a) and 3(b) show the microscope images in transition and waist region of the fabricated MC. The diameter of the uniform waist region each fiber of is ~2.45 μm as seen from Fig. 3(b), and the length is ~1 cm. Moreover the length of whole transition regions is ~3 cm, and the equivalent and averaged coupling length is ~2.5 cm.. Figure 3(c) demonstrates multiple interference peaks of a period of oscillating spectrum which can be explained by the interference of low-order symmetric and anti-symmetric supermodes in the coupling region. Besides, a slow modulation of the spectral envelope can be found on account of the different coupling coefficients for x and y polarizations [20]. The inset of Fig. 3(c) shows the output spectra from Port 3 of the sensor with 80 mA electric current and 0 mT or 10 mT magnetic fields.

Based on the output spectrum of Port 3 seen from Fig. 3(c), we can estimate the coupling length to be ~2.4 cm, which is the averaged coupling length including the waist and transition regions and coincides with the experimental measurement.

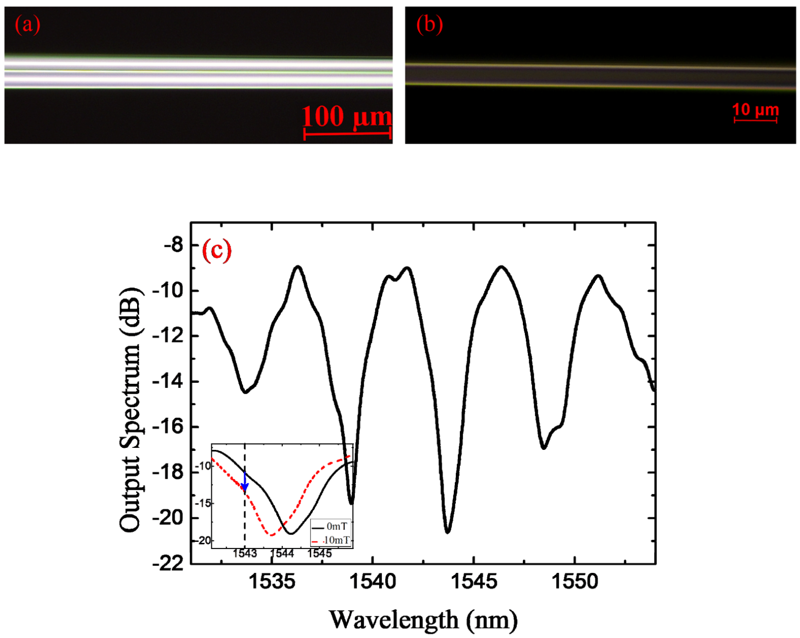

Fig. 3. Microscope images of (a) the transition region and (b) the waist region of the MC, the diameter of each coupled microfiber is 2.45 μm; (c) The output spectrum of the sensor without any magnetic field and electric current. The inset shows the output spectra from Port 3 of the sensor with 80 mA electric current and 0 mT or 10 mT magnetic fields.

3.1 Magnetic field sensor

The sensitivity of magnetic field is measured with the apparatus as shown in Fig. 1. The laser at 1543 nm injects into Port 1, and exits from the twin-output Port 3 and Port 4. We read the power from the twin power meters. The given electric current flowing through the Al wire is 80 mA, and the power read from the twin power detectors is stable. Then the sensor subjects to Lorentz force when placed under a perpendicular magnetic field from 0 mT to 10 mT. The Lorentz force causes small changes in refractive index and coupling length. Thereby, power distribution between the twin-output Port 3 and Port 4 in Eq. (1, 2) changes. Seen from the output spectrum of Port 3 in the inset of Fig. 3(c), light intensity of Port 3 in the wavelength of 1543 nm decreases when the sensor subjects to the Lorentz force. From the movement of the wavelength spectrum, the magnetic field sensitivity can reach 51.3 pm/mT when 80 mA

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electric current is applied, which is twice as high as the sensitivity of the configuration described in Ref [11].

After data analysis, the Lorentz force makes Γ change synchronously in Eq. (4). Figure 4 shows Γ dependence on magnetic field in the wavelength of 1543 nm in ascending and descending directions when the given electric current is 80 mA. As we can see from Fig. 4, Γ varies almost linearly with the magnetic field in both ascending and descending directions and matches well with each other. Using the sensor, we measured a magnetic field sensitivity of ~0.0496 mT^{-1} under 80 mA perpendicular electric current.

As seen from Fig. 2, the force sensitivity is ~1890 N^{-1} when the microfiber diameter is ~2.45 μm. We can calculate the longitudinal force (~3x10^{-5} N/mT) from the applied transverse Lorentz force. Thus, the magnetic field sensitivity can be theoretically estimated as 0.057 mT^{-1} of our MC device. The sensitivity can be increased by optimizing the MC diameter.

Due to the limit of our magnetic field generator, the magnetic field can't be conducted rapidly and that is why we didn't test the response time. But the Lorentz force results in mechanical stretching and spectral shift. Considering the response time is mainly limited by the mechanical response, we estimate the response time to be less than one second. As for the detection limit, it can be calculated as $\delta\Gamma/S$, depending on both the sensitivity (S) and the deviation of Γ ($\delta\Gamma$). Theoretically, $\delta\Gamma$ only depends on the resolution of the power meter (1nw. S145C, Thorlabs). The detection limit can be as small as 7.09 nT when the sum of the output power $P_3 + P_4 \approx 5.69$ mW. However, in the practical measurements, the output intensity is not absolutely stable because of the environment fluctuations (temperature, air flow, etc.). $\delta\Gamma$ depends on not only the resolution of the power meter but also the fluctuation of the output intensity. In our measurement, the fluctuation of the output intensity is < 0.02 mW. Then we can get the detection limit of ~0.14 mT which is analogous to the PCF based magnetic field sensor described in Ref [11]. We can improve the detection limit by downsizing our MC to get a more compact device and packaging it with a glass tube to avoid environment perturbation.

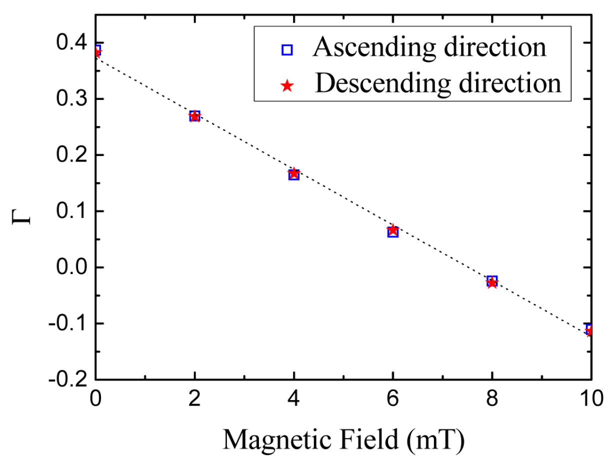

Fig. 4. Γ dependence on magnetic field in the wavelength of 1543 nm under 80 mA electric current in ascending and descending directions. The curve represents the linear fitting of the data.

3.2 Electric current sensor

The sensitivity of electric current is tested with the same apparatus as shown in Fig. 1. The electric current flowing through the Al wire varies from 0 A to 0.43 A under a static magnetic field or not. The power distribution between output Port 3 and Port 4 will change due to the distortion of the Al wire from not only the effect of Lorentz force but also thermal expansion.

The heat is generated by the electric current, and results in the distortion of the Al wire. The distortion causes small changes of refractive index and coupling length. First, we measure the sensitivity without the magnetic field (0 mT). The strain acting longitudinally on the MC rises when the electric current increases. Figure 5 shows Γ dependence on electric current in the wavelength of 1543 nm in ascending and descending directions when the given magnetic field is 0 mT. Γ varies almost linearly with the varying electric current in both ascending and descending directions and matches well with each other. In theory, heat generating by electric current is linearly to the square of the current. However, because the distortion is the result of the heat combined with the interaction of the optical fiber, Γ is almost linearly with the current from the experiment data, seen from Fig. 5. Using the sensor, we measured an electric current sensitivity of ~1.0899 A^{-1} under 0 mT.

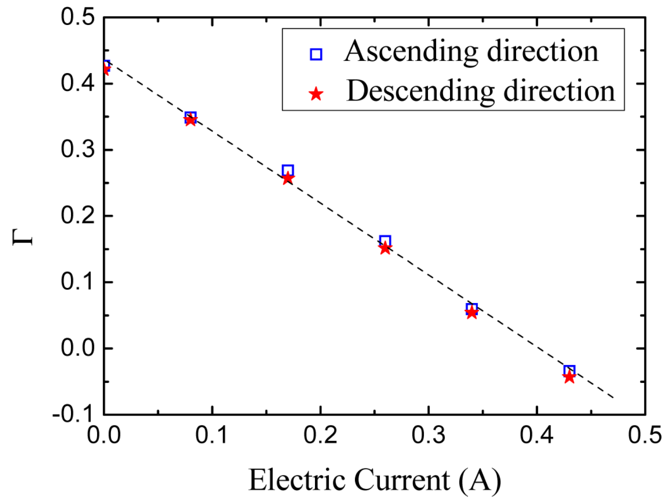

Fig. 5. Γ dependence on electric current in the wavelength of 1543 nm under no perpendicular magnetic field in ascending and descending directions. The curve represents the linear fitting of the data.

Then we also measure the sensitivity by setting the perpendicular magnetic field as 2 mT. The Lorentz force and thermal expansion rise simultaneously when the electric current increases. Figure 6 shows Γ dependence on electric current in the wavelength of 1543 nm in ascending and descending directions under 2 mT magnetic fields. As we can see from Fig. 6, Γ varies almost linearly with the varying electric current in both ascending and descending direction and matches well with each other. Using the sensor, we measured an electric current sensitivity of ~1.9919 A^{-1} under 2mT perpendicular magnetic fields. With comparison and analysis, due to the existence of the magnetic field, the Lorentz force enhances the electric current sensitivity. Obviously, if we increase the magnitude of the applied magnetic field, we can realize a higher electric current sensitivity.

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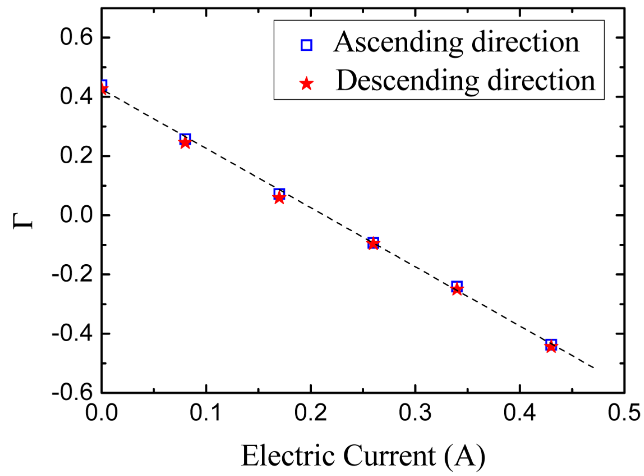

Fig. 6. Γ dependence on electric current in the wavelength of 1543 nm under 2 mT perpendicular magnetic fields in ascending and descending directions. The curve represents the linear fitting of the data.

To make our MC sensor practical to a real environment, we need to package the MC and the Al wire into a small glass tube, and seal both ends of the tube. Then the device can be well protected to avoid damaging and the influence of air flow.

Moreover, temperature stability is another key issue for practical applications. Two methods can be adopted. The first is that we could utilize a second microfiber device which is sensitive to ambient temperature to realize temperature compensation. Inevitably it could make the system more complicated. The second method is to utilize specialized polymer film with negative thermal-optic coefficient to coat the MC. At a special diameter of the coupler, the negative thermo-optic effect can compensate other thermal effects to counteract the temperature influence as much as possible.

4. Conclusion

In this work, a new kind of MC based differential twin receiving fiber-optic magnetic field and electric current sensor is proposed. It takes advantages of the influences of the Lorentz force induced by the magnetic field and the thermal expansion caused by the electric current when electric current flows through the metal Al wire. The sensor is low-cost and easy to be fabricated, without any intrinsic magnetic hysteresis and saturation effect. The sensor utilizes the ratio of the difference to the sum of the output signals from the twin-output ports. This approach eliminates the dependence on the perturbation of incident light power. Using our proposed sensor, we measured a magnetic field sensitivity of ~0.0496 mT^{-1}, current sensitivity of ~1.0899 A^{-1} without any magnetic field, with good repeatability.

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