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Mach-zehnder interfermeter magnetic field sensor based on magntic fluid and cladding-etched fiber

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Abstract. A Mach-Zehnder interferometer magnetic field sensor based on magntic fluid (MF) and cladding-etched fiber was presented in this paper. Theoretical analyses and experimental results show that the interference spectrum had drifted following the change of the external magnetic field which can change the MF refractive index and the phase difference between the fiber base model and the higher order cladding mode.When the external magnetic field varies in the range of 30mT—120mT,the interference spectrum shift sensitivity is up to 35pm/mT and has good linearity.

Key words. Wave-guide fiber optics, fiber sensor, mach-zehnder interfermeter, magntic fluid, magnetic field sensing.

1. Introduction

All along, fiber optic sensors have attracted much attention in the field of sensing because of their simple structure, small size, sensitive response to external conditions, and anti electromagnetic interference[1-3].Magnetic fluid is a kind of magnetic nano material, it has the fluidity of liquid, in external field, exhibit unique optical transmission properties, the optical properties of application in the field of optical sensing has attracted a lot of attention of researchers [4-6].In the field of magnetic measurement, it has been reported that a magnetic field sensor is fabricated by using

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the controllable refractive index characteristics of magnetic fluid and combining the optical fiber Fabry-Perot (F-P) resonant cavity structure [7,8] or the birefringence effect [9] of magnetic fluid.The former makes the F-P cavity with photonic crystal fiber or high reflecting film on the optical fiber end surface. The latter requires a bias device, a polarization controller and other attached devices, which are also expensive and complicated to operate.

In this paper, a Mach-Zehnder based interferometric magnetic field sensor is constructed, which is cascaded by two peanut-shape structures [10].The cladding of the fiber between the two structures by chemical corrosion, reduce the fiber cladding diameter, to enhance the fiber-optic evanescent field interaction with the surrounding medium, and the magnetic fluid in environmental medium, using controllable refractive rate characteristics of magnetic fluid, by modulating the measured magnetic field changes in refraction coated interference arm external magnetic fluid the rate of change of ambient refractive index caused by interference spectrum changes, so as to realize the measurement of magnetic field.

2. Measuring principle and sensor making

Schematic diagram of sensor structure as shown in Figure 1.The two optical fiber peanut-shape structures were cascaded, and the simulation analysis showed that [10] in the fiber peanut-shape structure, some of the energy in the core matrix was coupled to the higher-order cladding mode when the core-mode LP_{01} was propagated to the first structural peanut1 in the fiber. and transport in the package layer, after transmitting a distance to the second structure Peanut2, the High-order cladding module is coupled back to the fiber core, and the phase difference between the high order cladding mode and the fiber core base mode LP_{01} in the fiber core is peanut2, so the two beams of light interfere, An on-line optical fiber Zehnder interferometer is formed

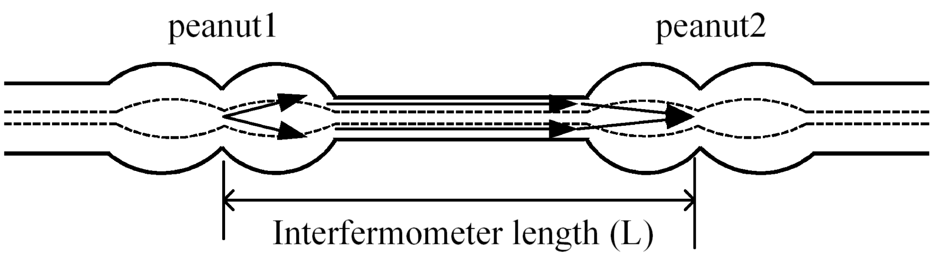

Fig. 1. Structure of Mach-Zehnder interferometer based on peanut-shape structure

According to the interference principle, the phase difference Φ^mbetween the higher order cladding modes coupled to the fiber core and the fiber core module remaining in the core can be expressed as [11];

$$\delta\lambda_m = \frac{2\delta n_{eff}^m}{2N+I} \tag{1}$$

Among them ,Δn^m_{eff} is the effective refractive index difference between the fiber core mode LP_{01} and the higher-order cladding mode LP_{0m}, L is the length of the interference arm between peanut1 and peanut2, and lambda is the input wavelength. Thus, the intensity of the interference signal can be expressed as [12]:

$$I = I_{CO} + I_{CL} + 2\sqrt{I_{CO} I_{CL} \cos(\Phi^m)} \tag{2}$$

In this case, $I_{CO}$is the light intensity propagating in the fiber core, $I_{CL}$is the light intensity which spreads in the cladding layer. When the phase difference φm exactly equals (2n+1) π, where n is an integer, the light intensity of the interference signal reaches the minimum value. At this point, the central wavelength of the trough of the N-level interference stripe in space can be expressed as:

$$\lambda_n = \frac{2\Delta n^m_{eff} L}{2N+1} \tag{3}$$

From the formula (1), it can be seen that the central wavelength of the spatial interference trough is related to the effective refractive index difference of the core core mode LP_{01} and the higher-order cladding mode LP_{0m} and the length of the interference arm L.

Some arm length L remain unchanged, according to the controllable refractive index of the magnetic fluids with the characteristics of external magnetic field increases, the refractive index of magnetic fluids increases[13], magnetic fluid as the medium is covered with the environment of the interferometer, increase its refractive index will lead to higher order propagating in the cladding of the fiber cladding mode LP_{0m} the increase of the refractive index (assuming the increase δn^n_{eff}), but the effective index of the core mode of LP_{01} transmission in the core was affected by the external environment is very small, basically unchanged, so the effective index of the core mode of LP_{01} and high order cladding mode LP_{0m}rate differential will decrease δn^n_{eff}. According to the formula (3), when the intensity of the interference signal(I) reaches the minimum, the center wavelength of the N interference fringe trough in the interference signal will drift to the short wavelength direction due to the decrease of the effective refractive index difference(Δn^m_{eff}). The drift quantity can be expressed as:

$$\delta\lambda_m = \frac{2\delta n^m_{eff}}{2N+I} \tag{4}$$

The external magnetic field measurement can be realized by monitoring the drift of the center wavelength of the n-level interferometric stripe trough with the change of the external magnetic field.

In order to increase the interference fringe troughs center wavelength drift capacity, higher sensor sensitivity, according to the formula (4), increase the fiber core base model $LP_{0m}$with higher order cladding mode LP_{01} change of effective refractive index difference method is effective. Under the condition of the same external magnetic field, because the smaller the diameter of the optical fiber, the evanescent wave propagation in optical fiber surface will be strengthened, so when the external environment refractive index change of higher order cladding mode LP_{0m} effective refractive index is more vulnerable, making δn^n_{eff}increased, so as to improve sensor sensitivity.

In order to reduce the diameter of the interferometer's sensing arm, the method of chemical etching is adopted in actual fabrication. First of all, the use of ordinary commercial optical fiber splicer (KL300T) on both ends of the cut flat ordinary single-mode fiber with high energy discharge, the fiber end formed shape, as shown in Figure 2 (a), then in accordance with the ordinary single-mode fiber welding for welding of two fiber ball, thereby forming a peanut-shape structure, as shown in Figure 2 (b). In a single-mode fiber on L interval length of two peanut-shape structure, making the interferometer, two peanut-shape structure completely according to the discharge energy and the same step, try to ensure the symmetry of the structure. Finally, the HF with 10% concentration was used for chemical etching of the optical fiber between two peanut-shape structures, and the proper etching time was controlled. Finally, an on-line fiber Mach-Zehnder sensor with cladding corrosion was fabricated.

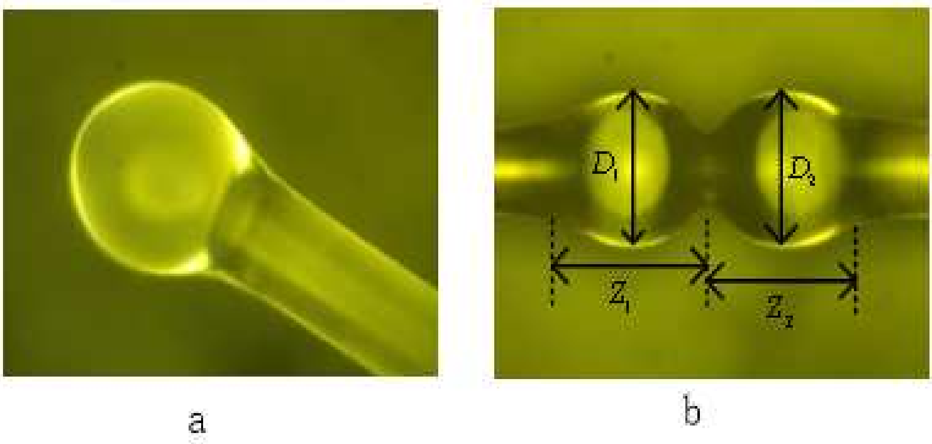

Fig. 2. microstructure of optical fiber peanut-shape structure (a)After high energy discharge treatment (b) Peanut-shape structure of weld forming

3. Magnetic field sensing experiment and discussion

The magnetic sensor experiment device as shown in Figure 3, the interferometer made to set 0.5mm diameter capillary, using the siphon principle to ionic water-based Fe_3O_4 magnetic fluid($\Phi_V = 2\%$) prepared by Massart infusion into the capillary, and then placed in the interferometer is measured in a magnetic field, and at the tail end of hanging a mass of about 5 grams of light, the fiber free tension due to the suspension in the process of measurement is always the same light and the quality of only a few grams, so the light can affect the interference spectrum change ignored. The experimental light source is output by laser with spectrometer Si720, and the interference spectrum is detected by Si720 after interferometer. The measured magnetic field is supplied by an CH-50 electromagnet, and the maximum magnetic field strength is 700mT.

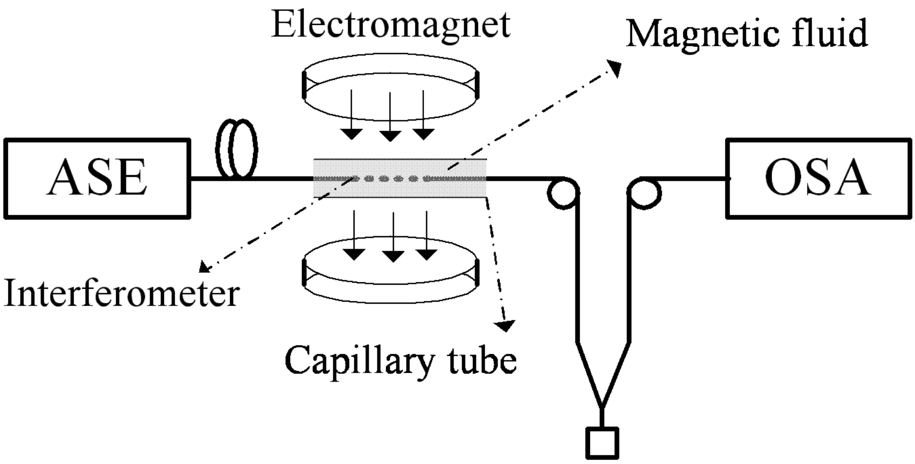

Fig. 3. magnetic sensing experiment device diagram

In the experiment, the arm length L= 35mm, the first peanut-shape structure D_1=215 μm, D_2=213μm, Z_1=226μm, Z_2=235μm;The second peanut-shape structure D_1=208μm,D_2=210 μm,Z_1=232μm,Z_2=229μm,two peanut-shape structures are basically symmetric.With concentration of 10% HF to corrosion of the interference of the interferometer arms, control of corrosion time, corrosion to interfere in arm fiber diameter for 100μm and 60μm, interferometer with deionized water after cleaning, in accordance with figure 3 experimental device has two kinds of the diameter of the interferometer for measuring magnetic field sensor.

Fig. 4 is the interference fringes formed by the interferometer, because there are two or more higher-order cladding modal core modes in the fiber, in which only one High-order cladding mode dominates, so the interference fringes formed are irregular sine signals [10]. At the same time, due to the different diameter of the interference arm, the effective refractive index difference between the fiber core and the higher order cladding mode is different, so the interference fringes have a change before and after the interference arm corrosion. In the range of the effective measurement wavelength range of the spectrometer Si720, the 1520nm–1570nm of the visible interference fringes is three, for the convenience of observation, the center wavelength of the middle one interference fringe is selected as the observation object.

Adjusting the external magnetic field is 0 mT to 220 mT increase and then decrease gradually, at the same time the real-time observation records interference fringe trough center wavelength drift, in order to eliminate the effects of temperature in the process of experiment, the whole experiment process is conducted in a constant temperature of indoor, the temperature is 25 .

The experimental results are shown in fig.5 and fig. 6, and it can be seen that, with the increase of the external magnetic field, the wavelength of the interference

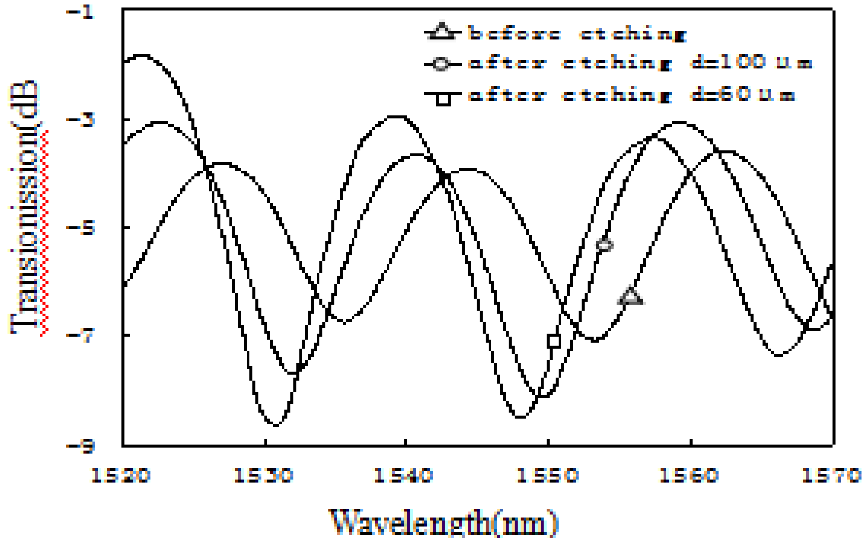

Fig. 4. mach-zehnder interferogram based on the fiber peanut-shape structure

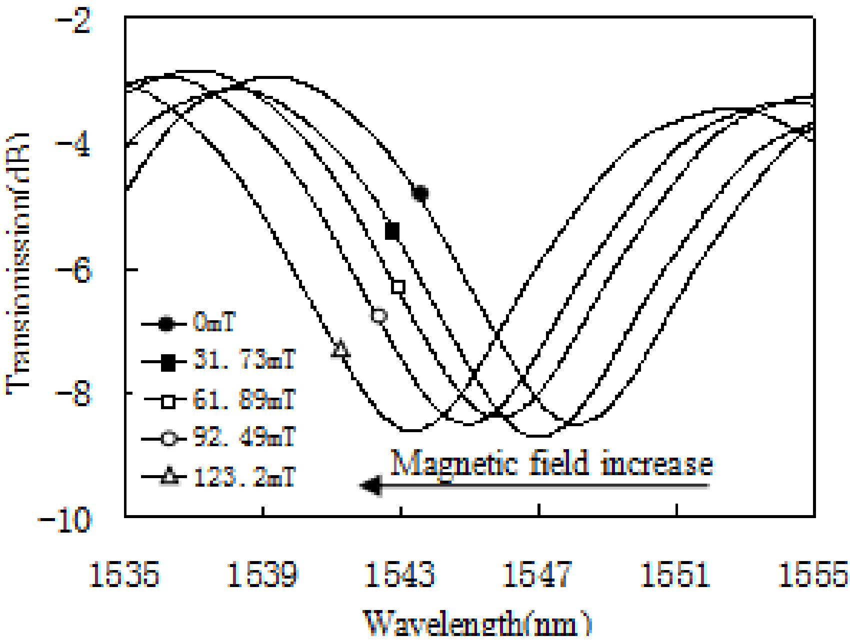

Fig. 5. mach-zehnder interference spectra of the interference arm diameter of 60 mum

fringe trough has shifted to the short wave direction, which is consistent with the

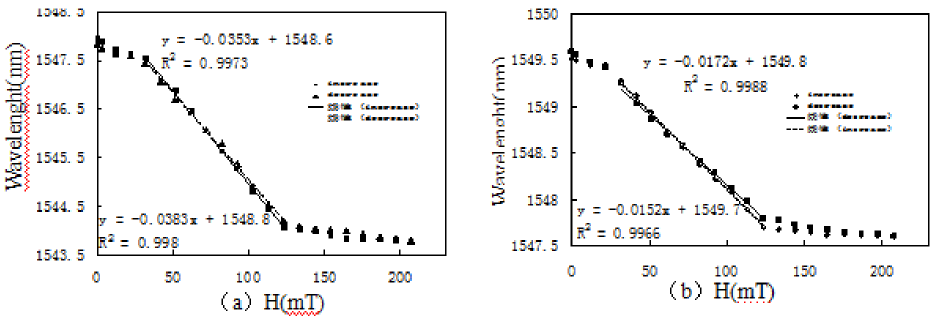

Fig. 6. mach-zehnder magnetic sensing characteristics based on the fiber peanut-shape structure (a)Diameter 60μm of interference arm (b)Diameter 100μm of interference arm

theoretical analysis. When the external magnetic field is between 30mT and 120mT, the sensor sensitivity of the interference arm diameter of 60μm interferometer can reach 35pm/mT, and the linearity is better. However, during the change of magnetic field from 0mT to 220mT, the change of magnetic field and the wavelength drift of the center of the trough are not linear relation, which is related to the variation of magnetic control refractive index of magnetic fluid [13].

Magnetic fluid is a kind of suspension with magnetic particles dispersed evenly. In experiment, Fe_3O_4 magnetic particles are obtained by chemical coprecipitation. The average particle size(x_g) is 13.9nm, and the geometric standard deviation($\lg x_g$) is 0.12. When the external magnetic field is small (H<30mT), the interaction between particles is weak to insufficient to make a magnetic particle in a magnetic fluid into a chain,Fe_3O_4 magnetic particles in the magnetic fluid are evenly distributed, and the magnetic field distribution of particles before little change, as shown in Figure 7 (a) shows, so the smaller magnetic field effect weak magnetic fluid of refraction, so no obvious interference fringe center wavelength drift. With the gradual increase of the magnetic field, enhance the interaction between particles and Fe_3O_4 magnetic particles of larger particles formed with short chain, and along the magnetic field direction with the magnetic field increasing, small magnetic particles in a magnetic fluid in magnetic field also gradually into a chain, and short chain formed long chains, as shown in Figure 7 (b), (c) shows, this change of magnetic fluid in micro structure of the refractive index change, so in a certain range (30mT<H<120mT), with the increase of the magnetic field, the interference fringes trough the wavelength drift changed greatly. When the external magnetic field increases to a certain value (H>120mT), magnetic fluid in magnetic particles almost all have been involved in the formation of long chain, as shown in Figure 7 (d), then, even if the magnetic field continues to increase, but the micro structure of magnetic fluid in the magnetic fluid almost does not change, change of refractive index is also reduced therefore, the interference fringes trough central wavelength drift again tends to be stable.

In addition, the experimental results also can be seen in the external magnetic field decreases from 220mT to 0mT in the process of repeated interference fringe center wavelength drift curve trough is better, because the water-based ionic Massart

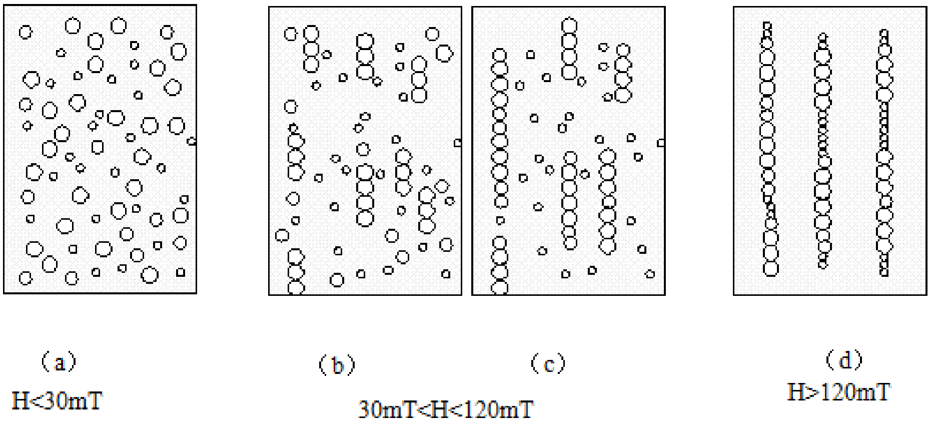

Fig. 7. schematic diagram of microstructure change of magnetic fluid under external magnetic field

prepared Fe_3O_4 magnetic fluid particle geometry size and fluid particle size, Fe_3O_4 magnetic particles and magnetic fluid were paramagnetic magnetic [14].

Compare fig.6 (b) and (c), it can be seen that the interferometer with a 60μm diameter is significantly higher than that of the 100μm interferometer, indicating that the smaller the diameter of the interference arm is, the higher the sensitivity of the magnetic field sensor is, but the smaller the diameter will reduce the mechanical strength of the interferometer, which is not easy to manufacture and package.In order to improve the sensitivity of the sensor, we can study the performance of magnetic fluid.

4. conclusion

Through theoretical analysis and experiments show that strain - shape based on the magnetic structure corrosion cladding fiber Mach - Zehnder interferometer in magnetic field sensor with good properties, and can make compact structure, low cost, the magnetic field sensor used for measuring parameters such as magnetic field and electric current. If the magnetic-controlled refractive index of magnetic fluid can be further optimized, the sensor with higher sensitivity, magnetic field or current measurement can be produced.

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