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2014

Zheng, Y., Dong, X., Yang, R., Zhang, S., Chan, J. C. C., & Shum, P. P. (2014). Magnetic field sensor with optical fiber bitaper-based interferometer coated by magnetic fluid. *IEEE sensors journal*, 14(9), 3148-3151.

<https://hdl.handle.net/10356/104941>

<https://doi.org/10.1109/JSEN.2014.2325945>

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Magnetic Field Sensor with Optical Fiber Bitaper-Based Interferometer Coated by Magnetic Fluid

Yangzi Zheng, Xinyong Dong, Runguang Yang, Shuqin Zhang, Chi Chiu Chan and Perry Ping Shum

Abstract—An optical fiber magnetic field sensor is demonstrated by using a waist-enlarged fusion bitaper-based optical fiber Mach-Zehnder interferometer (MZI) coated by magnetic fluid (MF). Since refractive index (RI) of the MF is sensitive to magnetic field, differential effective refractive index of the sensing fiber and hence transmission spectrum of the MZI are modulated. In addition, structural pattern state of the nano-scaled magnetic particles in the MF changes with magnetic field strength, leading to variation in contrast of the interference pattern through scattering-induced loss of the cladding modes which interfere with the core mode. By monitoring wavelength shift or intensity change of a transmission dip of the MF-coated MZI, magnetic field strength measurement is realized with sensitivity up to -24 pm/Oe or 0.085 dB/Oe for wavelength and intensity measurements, respectively.

Index Terms—Optical fiber sensors, magnetic field sensors, magnetic fluid, Mach-Zehnder interferometer.

I. INTRODUCTION

It is well-known that optical fibers are made from silica that makes optical fiber devices are less susceptible to electromagnetic interference. However, magnetic field measurement could be realized by combining optical fibers with magnetic materials, such as magnetic fluid (MF), a colloid that contains magnetic nanoparticles (e.g. Fe_3O_4 , MnFe_2O_4 , etc.) dispersed in a suitable liquid carrier such as water, oil or ester [1]. The nanoparticles will agglomerate and further form chains and columns when external magnetic field is applied. This field dependent structural pattern of MF will result in versatile magneto-optical effects, including Faraday effect, super-paramagnetic effect, magnetic field-dependent birefringence and refractive index (RI) [1, 2]. MF based optical fiber magnetic field sensors have attracted lots of attention in recent years by using different sensing structures, e.g., MF-coated tapered optical fibers [3], MF-coated fiber gratings [4-6], MF infiltrated optical microstructure fibers [2, 7-9], etc. As a kind of compact, easily fabricated and highly sensitive optical fiber structure, in-line Mach-Zehnder interferometers (MZIs), which based on the interference between the

Fig. 1. Experimental setup of the proposed optical fiber magnetic field sensor. Inset: optical microscope image of the bitaper.

core and cladding modes in an optical fiber, have also been used as magnetic field sensors by cooperating with MF [10-12]. Either no core fibers (NCF) or cladding-etched multimode fiber have been used to form the in-line MZIs that may add to the manufacture difficulty and cost as well. We also find that the contrast ratio of the interference pattern in the reported works is relatively low and keeps reducing with magnetic field strength. That may lead to low accuracy and even failure in measurement.

In this Letter, an optical fiber magnetic field sensor by using a MF-coated waist-enlarged fiber bitaper (WEFB) based in-line MZI is proposed and experimentally demonstrated. By monitoring wavelength shift or intensity change of a transmission dip of the MF-coated MZI, magnetic field strength measurement is realized with sensitivity up to -24 pm/Oe or 0.085 dB/Oe for wavelength and intensity measurements, respectively. The whole sensing head can be easily made from the same single-mode fiber by using a normal optical fiber fusion splicer. And we find the contrast ratio of the interference pattern is relatively higher and increases with the magnetic field strength. That makes our sensor performs better when the magnetic field strength becomes higher.

II. SENSOR FABRICATION AND PRINCIPLE

Fig. 1 shows the experimental setup of the proposed optical fiber magnetic field sensor, including the schematic diagram of the sensor head, which is formed by two identical WEFBs cascaded along a single-mode fiber with a certain separation. The magnetic field was generated by using an electromagnet magnet and its strength was adjusted by changing the magnitude of the driving current. A gaussmeter was used to measured magnetic field strength in a real-time manner for the purposed of calibration [10]. A broadband light source (BBS) and an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a resolution of 0.02 nm were used to measure transmission spectrum of the MZI sensor.

The WEFBs were fabricated by using a fusion splicer (Fujikura FSM-60s). To improve the accuracy of fiber core alignment, SM-AUTO splicing mode was used rather than the manual splicing

This work was supported by the National Basic Research Program of China (973 Program) under Grant No. 2010CB327804, and National Natural Science Foundation of Zhejiang Province, China under Grant No. Z13F050003.

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Fig. 2. Response of the MZI to surrounding refractive index.

mode used in [13] and [14]. To form a waist-enlarged part, the parameter “overlap” was changed from 15 μm to 140 μm while other parameters were not changed. The achieved WEFB, with a photo shown in Fig. 1, has a maximum diameter of 169.1 μm and a tapering length of 394.9 μm . The fiber separation between the two WEFBs is ~ 13 mm. The so-formed MZI structure was then sealed in a capillary tube, which is filled with MF (Hinano-FFE3). The inner diameter and length of the capillary tube are 1 mm and 50 mm, respectively. The MF we used is a highly stable ester based ferrofluid containing Fe_3O_4 nanoparticles with an average diameter of ~ 10 nm. The infiltration of MF into the capillary tube was carried out by using an injection syringe rather than by capillary force, because the ester-based MF has large viscosity of ~ 80 cp, which is much larger than that (< 5 cp) of the water-based MFs. After infiltration, the capillary tube was sealed from the both ends with epoxy resins.

When the core mode propagating in the lead-in SMF encounters the first bitaper, cladding mode is excited due to the waveguide disturbances. This cladding mode interferes with the residual core mode at the second bitaper to generate an output interference pattern with a free spectral range determined by the phase difference between the two modes. The phase difference is simply given by [13, 15]

$$\Phi = 2\pi(n_{\text{core}} - n_{\text{clad}})L / \lambda = 2\pi\Delta n / \lambda \quad (1)$$

where n_{core} and n_{clad} are the effective refractive indices of the core and cladding modes respectively. L is the distance between the two bitapers, and λ is the operation wavelength in vacuum. The output optical intensity of the MZI can be expressed as

$$I(\lambda) = I_{\text{core}} + I_{\text{clad}} + 2\sqrt{I_{\text{core}}I_{\text{clad}}} \cos \Phi \quad (2)$$

where I_{core} and I_{clad} are the light intensity of the core and the cladding modes, respectively. When the surrounding RI varies, n_{clad} will be modified, leading to the variation in phase difference and hence wavelength shift of the transmission spectrum. When the MZI is immersed in the MF and external magnetic field is applied, RI of the MF, and hence n_{clad} of the fiber, will be changed and modulated by the magnetic field intensity due to the field dependent structural pattern of the nanoparticles in the MF [4]. Thus magnetic field measurement can be realized by detecting wavelength shift of the interference spectrum of the MZI.”

III. EXPERIMENTAL RESULTS AND DISCUSSION

Response of such a MZI sensor head (without MF-coating) to surrounding RI was tested first in the experiment. We used glycerol solutions with different concentrations [13] to change RI around 1.44, which is about the value of MF when there is no magnetic field applied [2]. The measured transmission spectra, as shown in Fig. 2, indicate that the transmission dip at ~ 1539 nm was shifted by 9.3 nm to shorter wavelength when surrounding RI was increased from 1.4012 to 1.4514. The corresponding sensitivity is up to -116 nm/RIU,

Fig. 3. Transmission spectra measured at different magnetic field strengths.

which shows good potential for magnetic field measurement via RI of the coated MF.

Then the MF-coated MZI sensor head (with maximum transmission dip at ~ 1511.4 nm) was tested under various external magnetic field strengths. Fig. 3 shows the measured transmission spectra when the magnetic field strength was changed between 0 and 240 Oe, which is limited by the capability of the magnetic field generator. It can be seen that wavelength of the transmission dip changes monotonically from 1511.4 nm to 1507.2 nm with increasing of the magnetic field strength. This is because RI of the MF surrounding the MZI was increased as a result of agglomeration of magnetic nanoparticles in MF when magnetic field was applied [16]. It affected n_{clad} in Eqs. 1 and 2 so that interference pattern of the MZI shifted spectrally.

The detailed variation of the transmission loss at the dip wavelength was also measured when magnetic field strength was varied in both ascending and descending orders between 0 and 240 Oe. The results are also shown in Fig. 4. The largest deviation between the two groups of data is less than 0.5 dB. Near linear response is achieved for the magnetic field strength between 80 and 240 Oe and the sensitivity is up to ~ 0.085 dB/Oe.

The measurement was carried out in both ascending and descending orders. The results, as shown in Fig. 4, agree very well with each other. The largest deviations are less than 0.1 nm and 0.5 dB for the wavelength and intensity measurements respectively, indicating good repeatability. The largest deviations are less than 0.1 nm and 0.5 dB for the wavelength and intensity measurements respectively, indicating good repeatability. The sensor shows nearly linear responses for magnetic field strength range upwards of 80 Oe. The sensitivity for wavelength measurement is -24 pm/Oe, which is lower than that achieved from MF-infiltrated microstructured optical fiber-based long-period grating (1946 nm/Oe) [8] but higher than

Fig 4 Responses of transmission dip wavelength and loss to magnetic field strength.

Fig. 5 Responses of transmission dip wavelength and loss to temperature

that of the MF-coated MZI structure (-16.86 pm/Oe) [12]. The sensitivity for intensity measurement is ~ 0.085 dB/Oe, which is higher than that (0.042 dB/Oe) achieved by using MF-based microstructure optical fiber [7] and those (0.075 and -0.019 dB/Oe) achieved with NCF-based structures [10, 11].

The relatively low responses when magnetic field strength is lower than ~ 75 Oe are related to the initial magnetization process of the nanoparticles in MF. During this process, most of the nanoparticles only rotate themselves from random orientations to parallel to the magnetic field, and few connect to form chain-like clusters [5]. Under this situation, the influence of magnetic field to the MZI sensor head through MF is very weak, compared with that when the magnetic field is further increased to make the nanoparticles form chains and even columns. The initial magnetization strength depends on the type of MF, usually around tens of Oe. Here the relatively high value may also relate to the relatively large viscosity of the MF we used.

Along with the change in wavelength, the peak intensity and fringe visibility of the MZI also change with magnetic field strength (see Fig. 3). The visibility increases from 9.06 dB to 20.83 dB when the magnetic field strength is changed from 50 Oe to 240 Oe. This is much larger than what was observed in the case of using glycerol solution, where the variation in fringe visibility is less than 3 dB, as shown in Fig. 2. The reason we believe is related to the much larger absorption and scattering effects of the MF than that of the glycerol solution, which is a nearly transparent liquid. As we know that the structural pattern of the nano-scaled magnetic particles in the MF changes (from uniformly-distributed nanoparticles to chains and further to columns) with magnetic field strength [5, 6], so their absorption and scattering coefficients to the light propagating in the MF change accordingly. The intensity of the cladding modes of the MZI is therefore reduced by the coating MF through the evanescent field. In our case, initial intensity of the cladding modes part is relatively larger than that of the core mode part so the initial contrast of the interference pattern is only 9.06 dB. The absorption and scattering introduce some loss to the cladding modes through the evanescent field, so the both intensities tend to be closer. That enhances the interference and increases the contrast at the cost of a slight reduction at the top level of the interference pattern [6, 17].

To investigate temperature response of the sensor, we changed the temperature (with no magnetic field applied due to the experimental limitation) and measured variations of the wavelength shift and transmission loss of the MZI. The results, as shown in Fig. 5, indicate that the temperature sensitivity are 0.13 nm/ $^{\circ}$ C and 0.105 dB/ $^{\circ}$ C (corresponding to 5.58 Oe/ $^{\circ}$ C and 1.24 Oe/ $^{\circ}$ C) for the wavelength and transmission loss measurements, respectively. So the temperature effect cannot be neglected in the measurement of magnetic field, and in practical application, compensation or simultaneous measurement is preferred. The temperature response of the sensor is mainly related to the hydraulic pressure from the liquid volume expansion and the decreasing RI of MF with temperature augmentation [18].

IV. CONCLUSION

An optical fiber magnetic field sensor based on MF-coated in-line optical fiber MZI has been proposed and investigated. Magnetic field strength can be measured by monitoring wavelength shift or intensity of the transmission dip in the interference spectrum. Relatively high sensitivities of -24 pm/Oe and 0.085 dB/Oe have been achieved by using the two interrogation methods, and the measurements have shown good repeatability.

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