Optics Communications 374 (2016) 76–79

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Magnetic field fiber sensor based on the magneto-birefringence effect of magnetic fluid

Xueqin Lei [a,b], Jiajia Chen [a,b], Fuquan Shi [a,b], Daru Chen [a,b], Zhijun Ren [a,b], Baojin Peng [a,b,*]

[a] Institute of Information Optics, Zhejiang Normal University, Jinhua 321004, China
[b] Joint Research Laboratory of Optics of Zhejiang Normal University and Zhejiang University, Hangzhou 310058, China

ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form
8 April 2016
Accepted 18 April 2016
Available online 29 April 2016

Keywords:
Fiber optics sensors
Interferometry
Sagnac effect
Magneto-optical materials
Fibers
Polarization-maintaining

ABSTRACT

In this study, the magneto-birefringence effect of magnetic fluid (MF) is adopted to form an innovative fiber optic magnetic field sensor. The sensitive section is fabricated via a D-shaped microstructure inscribed in a high-birefringence fiber Sagnac loop with a femtosecond laser. The D-shaped microstructure facilitates good combination of the optical-fiber Sagnac interferometer with the magneto-birefringence effect of MF without suffering from absorption loss and manual alignment. Experimental results show the good performance of the magnetic field fiver sensor, particularly its high stable extinction ratio. Preliminary results are provided, and the magnetic field sensitivity of 0.0823 nm/mT can be further improved by increasing the depth and length of the D-shaped microstructure.

1. Introduction

Magnetic fluid (MF) is one of the most interesting magneto-optical materials. This fluid exhibits versatile magneto-optical properties, such as refractive index tunability, Faraday effect, birefringence effect, and dichroism effect [1–3]. Numerous MF-based optical fiber devices have been reported because of their light weight, compact size, and superior resistance to electromagnetic interference over that of their electronic counterparts. The refractive index tunability of MF-based sensors, which only surround a series of refractive-index-sensitive fiber structures with MF, has been extensively investigated. For instance, a series of optical fiber interferometers, such as Mach–Zehnder [2], Fabry–Perot [3], Sagnac [4], and multimode interferometers [5, 6], has been extensively investigated with long period grating [7], tapered fiber [8–10] and photonic crystal fibers [11, 18], etc. However, many problems remain. On the one hand, no subsequent practical processing exists, and the ideas remain in the experimental stage. On the other hand, the tunable range of the refractive index of MF under an external magnetic field is rather small, thereby limiting the sensitivities of MF-based magnetic field sensors. Moreover, the Mach–Zehnder fiber structure requires complex matching of the fiber length or equalization of optical intensity. The Fabry–Perot fiber structure, which is usually an open cavity, is limited by the transmission loss of MF [12].

The configuration of a Sagnac-based sensor, which has two beams completely through the same path in the fiber loop for interference, has numerous advantages over other optical fiber interferometers. However, the MF possesses a large birefringence coefficient and exhibits huge transmission loss because of the increase in the transmission length. Thus, applications based on the birefringence effect of MF are rarely reported. A Sagnac fiber magnetic field sensor based on the magneto-birefringence of MF film was first proposed by Zu in 2011 [13]. In 2014, the sensitivity of this sensor was improved from 16.7 pm/Oe to 592.8 pm/Oe when the birefringence of the MF film was magnified with a high-birefringence polarization-maintain fiber (PMF) [14, 15]. However, transmission loss remains, such as in a Fabry–Perot interferometer [16]. The sensor proposed in the aforementioned study is based on the dichroism and birefringence effects, whereas the sensor we propose is only based on the birefringence effect. The birefringence of MF is always accompanied by dichroism; thus,the output optical power is varied by changing the applied magnetic field strength. In addition, incorporating the MF film in the loop with two collimators is not favorable, and manual alignment issues that limit the application of MF occur in the reported sensors. The most important thing is that the sensitive section of these sensors cannot be extended to increase sensitivity, particularly in the sections with a high concentration of black-brown MF. The reason is that absorption loss occurs when the incident light directly passes through the dark reddish-brown colloidal solution

---

* Corresponding author at: Institute of Information Optics, Zhejiang Normal University, Jinhua 321004, China
E-mail address: jhpbj@zjnu.cn (B. Peng).

http://dx.doi.org/10.1016/j.optcom.2016.04.044
0030-4018/

(MF) [17]. This problem needs a solution for the optical applications of MF in the future. These scenarios contribute to the deterioration of device performance.

A femtosecond laser, which uses ultrashort pulse width and ultrahigh peak power, is a well-known tool for the microfabrication/nanofabrication of materials and is widely used in fiber sensing [18–21]. In this study, an in-line fiber magnetic field sensor based on the magneto-birefringence effect of MF is proposed to avoid the aforementioned limitations and provide good performance. The proposed sensor is fabricated with a femtosecond laser. The sensitive section of this sensor can be extended to increase sensitivity, whereas the thickness of the MF film is limited in the open cavity, particularly in the section with a high concentration of black-brown MF.

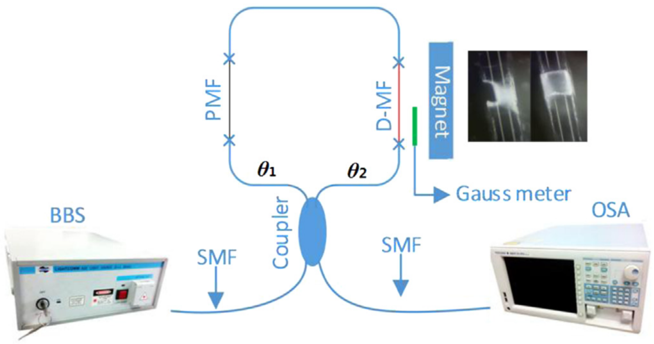

Fig. 2. Structure of the magnetic field fiber sensor based on MF.

2. Sensor structure and fabrication

The femtosecond laser used was a regenerative amplified mode-locked Ti: sapphire laser with pulse duration of 120 fs, central wavelength at 800 nm, and repetition rate of 1 kHz. The D-shaped trench under fabrication was translated using a computer-controlled *X*–*Y*–*Z* micropositioning stage with a resolution in nanometer scale. The fabrication was monitored in situ with a charge-coupled device. The three-step fabrication of the MF-filled D-shaped fiber Sagnac magnetic field sensor included the fabrication of the microstructure, encapsulation of the MF, and construction of the interferometer.

The microstructure was fabricated as follows. First, the average laser power was maintained at 45 mW. The cleaned sample of the uncoated single-mode fiber (SMF) was mounted on a translation stage. The laser beam was focused initially on the fiber core and then up to the outermost surfaces of fiber cladding by adjusting the *Z*-axis. The D-shaped cavity was created in a standard SMF with femtosecond laser ablation, in which the laser was scanned at a speed of 0.06 mm/s perpendicular to the fiber axis. Second, the focal point of the laser beam was moved toward the core axis with a step of 0.02 μm, and then the second scanning cycle was completed. This step was performed to smoothen and clean the machined surface. Thus, the D-shaped fiber with a depth of ~50 μm and a length of 0.1 mm was obtained Fig. 1(a). The finish depth closer to the fiber core, the higher the sensitivity would be. The depth of the D-shaped structure could be further increased to improve the sensitivity. Only 40% of the fiber cladding was ablated, and the fiber core was not destroyed. Thus, the light would not directly pass through the MF, and the performance of the sensor would not be affected by the absorption loss of the MF. Therefore, the length limit of the PMF could be extended by increasing the effective length of the MF when the sensitivity was improved. The Sagnac fiber magnetic field sensor could even be fabricated without cascading the PMF as we push it to an extreme. High sensitivity and flexibility are important for practical application in certain areas.

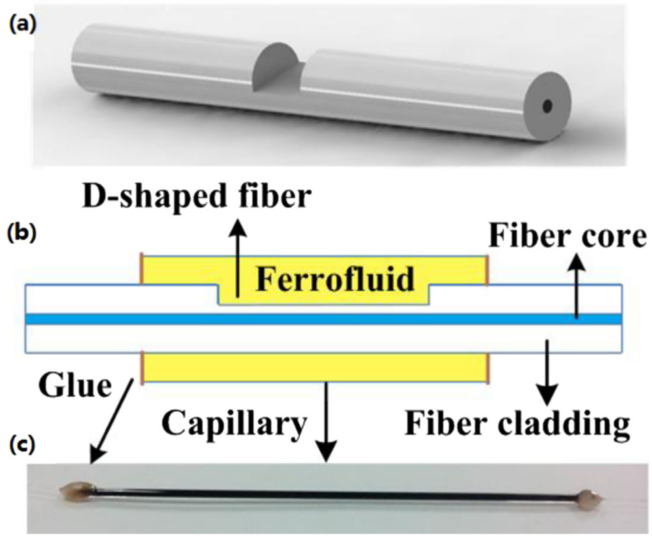

Fig. 1. Schematic of the MF-filled D-shaped fiber.

During the encapsulation of the MF, the D-shaped fiber was immersed in an MF-filled glass capillary tube and sealed with a glue gun to function as a magnetic field sensing probe. The schematic of the encapsulation and the image of the MF-filled D-shaped fiber are shown in Fig. 1(b) and (c) respectively. The oil-based MF (APGS12n, 250 MPa s in viscosity) provided by Ferrotec USA Corporation was used.

Finally, the sensing probe was spliced with a 78 cm-long PMF in a fiber loop, which was connected with a 3 dB coupler (2 × 2) to form a fiber Sagnac interferometer (Fig. 2). The light originated from a broadband-amplified spontaneous emission source (ASE-C/CL, LightComm Technology Co., Ltd) and was received by an optical spectrum analyzer (OSA; YOKOGAWA, AQ6375). This source was labeled as BBS in Fig. 1. The magnetic field was supplied perpendicular to the sensor probe through an electromagnet and was measured using a gaussmeter with a resolution of 0.01 mT. The experiment was conducted at room temperature (22 °C).

3. Operation principle of the sensor

The structure of the magneto-optic sensor based on an optical fiber Sagnac interferometer is shown in Fig.2. The sensor was fabricated with a D-shaped microstructure inscribed in a high birefringence fiber Sagnac loop with the femtosecond laser. The two counterpropagating beams, which were split with a 3 dB single-mode fiber (SMF) coupler, passed through the PMF and MF sections, recombined, and interfered at the coupler. The transmission spectrum was monitored with OSA at 0.02 nm resolution.

The combination of PMF with MF was considered an entire polarization component similar to an optical wave plate to simplify the analysis. The relative transmission spectrum T can be presented as follows using the Jones matrix method [15]

$$T = 2\sin^2(\theta_1 + \theta_2)\left[1 + \cos(\varphi_{\mathrm{PMF}} + \varphi_{\mathrm{MF}})\right] \tag{1}$$

where θ_1 and θ_2 are the angles between the polarization directions of counterpropagating beams and the equivalent fast or slow axis of the polarization component respectively. T is an approximate sinusoidal function of wavelength λ. $\varphi_{\mathrm{PMF}} = 2\pi B_P L_P/\lambda$ is the phase difference introduced by the birefringence effect (B_p) of the PMF over the fiber length (L_p). $\varphi_{\mathrm{MF}} = 2\pi B_m L_m/\lambda$ is the phase difference