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Magnetic field sensing based on fiber loop ring-down spectroscopy and etched fiber interacting with magnetic fluid

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ABSTRACT

A novel magnetic field sensing system based on fiber loop ring-down spectroscopy (FLRDS) and etched fiber interacting with magnetic fluid (MF) is proposed and demonstrated for the first time. The enhanced evanescent field effect in the sensing part was achieved by etching the fiber with hydrofluoric acid. The influence of diameters of etched fiber to the performance of the sensor was investigated and discussed. In the sensing system, the etched fiber surrounded by MF was used as the sensing head and on account of the tunable refractive index and absorption coefficient of MF, the transmission spectrum would change with the magnetic field strength. In this letter, the FLRDS sensing system was theoretically modeled and FLRDS technique was utilized to modulate the transmission spectrum. The sensitivity of magnetic field sensing was enhanced significantly. In the experiment, performances of the magnetic field sensing system were tested by applying different measured magnetic field. The final results indicated that a sensitivity of 12.56 G/μs was achieved.

1. Introduction

The measurement of magnetic field is of vital importance in a host of fields, such as navigation, environment monitoring, intelligent weapon, aerospace and smart grids, etc. [1]. Compared to electronic techniques employed in magnetic field detection, fiber-based magnetic field sensors have advantages of immunity to electromagnetic interference, small size, and low loss for long distance operation and so on [2]. For the present, various kinds of fiber-based magnetic field sensors have been reported including side-polished fiber Bragg grating (FBG) coated with thin film of iron or Terfenol-D [3,4], utilizing the Faraday effect in a highly terbium-doped fiber [5], multimode fibers with magnetic composite coating [6], a FBG for dynamic magnetic field detection exploiting magnetically induced circular birefringence [7], magnetic field sensors based on the integration of a high-birefringence photonic crystal fiber with a composite material made of Terfenol particles and an epoxy resin [8], etc.

On the other hand, versatile configurations of optical magnetic field sensors based on magnetic fluid (MF) have been intensively investigated in last few years. As a magneto-optical nano-material, MF has captured much research interest owing to its distinguished magnetic-optical effects, such as Faraday Effect, refractive index tunability, birefringence, tunable absorption coefficient, dichroism and field dependent transmission [9,10]. It is one kind of black-brown stable colloidal translucent liquid, which comprises solid nano-magnetic particles coated with surfactant suspending in appropriate carrier fluids; thus MF has the magnetism of solid magnet as well as the fluidity of liquid [11]. Compared with other materials for fiber magnetic sensors, such as the magnetostrictive materials [12–14], and the terbium-doped fiber [15], MF is easier to integrate with a fiber. Nevertheless, MF-based fiber magnetic sensors, either a special fiber (such as long period fiber gratings (LPFG) with D-shaped fiber [16], and no-core fiber [17]) or a special structure (such as s-tapered microfiber [18], fiber with up-tapered joints [19], and microfiber knot [20]) is needed.

In this letter, a novel optical fiber magnetic sensor based on fiber loop ring-down spectroscopy (FLRDS) and etched fiber interacting with magnetic fluid is proposed for the first time. The sensor could be simply fabricated by etching the fiber with hydrofluoric acid. The etched diameters of the fiber could be controlled by the immersing time. The influence of diameters of the etched fiber to the sensor's performance was investigated. The MF was used to act as the coating of the etched fiber. Due to the tunable refractive index (RI) and absorption coefficient of MF, the transmission spectrum would change with the magnetic field. Research on the new FLRDS technique has been proceeding well in recent years [21,22]. In a FLRDS, optical losses of a light pulse in a fiber loop induced by changes in a quantity are measured by the

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light decay time constants, so FLRDS is a time-domain sensing technique used to demodulate the transmission spectrum in this letter. FLRDS sensors have near-real-time response, multi-pass enhanced high-sensitivity, and relatively low cost [23]. In this paper, the magnetic-tunable refractive index properties and absorption coefficient transmission properties of MF were considered at the same time and the FLRDS was utilized to modulate the transmission spectrum, so the ability in the aspect of the sensitivity and anti-interference was enhanced significantly.

2. Operation principle of the sensor

2.1. Properties of the magnetic fluid

Magnetic fluid is a new type stable colloid which consists of magnetic nanoparticles dressed with surfactant and highly disperses in a liquid carrier. MF possesses a sea of unique optical properties. The tunable refractive index of MF was utilized in this letter to demodulate the magnetic field strength. The relationship between refractive index and magnetic field was investigated in the letter. As the chain-like structures of MF are easily formed under the magnetic field strength, the refractive index of MF will change with the increase of the magnetic field strength for the reason that the micro-structure variation of magnetic fluid would influence the refractive index. The relationship between the refractive index and the magnetic field was measured in the experiment and it is shown in Fig. 1. Fig. 1 indicates that refractive index of MF increases with the increase of the magnetic field strength and refractive index of MF will reach saturation when magnetic flux density exceeds 650 G, which means that the response range of magnetic fluid induced by magnetic field is from 0 G to 650 G. In our work, the water-based MF EMG507 (Ferrotec USA Corporation) was used. The nanoparticles in the MF are Fe_3O_4, and their nominal sizes are about 10 nm. Its particle volume concentration is 18%. Different dimensions of MF will influence the range of refractive index of MF, but the principle is still tenable.

2.2. Design and fabrication of the sensor

The etched fiber magnetic field sensor filled with magnetic fluid proposed in the letter was sealed in a glass capillary using epoxy glue. Structure of the proposed magnetic field sensor probe is shown in Fig. 2. Firstly, a single mode fiber (SMF) with a 20 mm part without coating layer was slowly inserted into glass capillary from one end. Secondly, the hydrofluoric acid was filled into the tube by capillary action. The step was in order to etch the fiber. The cladding diameter of etched fiber was controlled by the time of

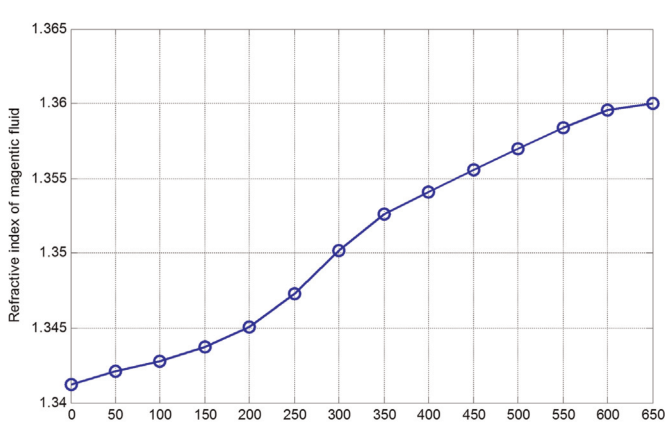

Fig. 1. Relationship between the RI of MF and magnetic field strength.

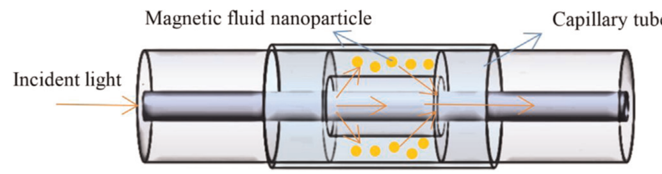

Fig. 2. Structure of the proposed magnetic field sensor.

erosion process and was measured with a microscope. Thirdly, the MF was filled into the tube after finishing the etching procedure. All the operations were achieved under a 6-dimension adjustment frame and a microscope. Finally, the both ends of the glass capillary were sealed with epoxy glue.

A water-based magnetic fluid (EMG 507, Ferrotec) with a particle volume concentration of 18% was used in the experiment. The nanoparticles in the magnetic fluid are Fe_3O_4 with an average diameter around 10 nm. The magnetic field supplied by an electromagnet was employed perpendicularly to the propagation of the light. The intensity of the applied magnetic field was adjusted by altering the supply current and calibrated by a Gauss meter (YK-450A).

2.3. Sensing structure and principle

2.3.1. Sensing structure

The experimental setup of the magnetic field sensing system based on an etched fiber surrounded by MF and FLRDS is shown in Fig. 3. The system consists of a C-band tunable wavelength Laser (TWL-C-R, Optilab, LLC.), an electro-optic modulator (JDS Uniphase Corporation), a function/arbitrary waveform generator (DG5352, RIGOL), an optical isolator, two couplers, an etched fiber surrounded by magnetic fluid (magnetic fluid concentration of $C=18\%$, EMG507, Ferrotec (USA) Corporation), a couple of electromagnetic coils that specification is 15×16 cm, a DC power, a Gauss meter, a high-speed photo-detector (OE455, LeCroy), a 3 km single mode fiber (SMF-28e, Corning) and an oscilloscope (640Zi, LeCroy).

Operating principle of the novel optical fiber magnetic field sensing system based on an etched fiber surrounded by magnetic fluid and FLRDS is described as follows. The signal generator sends pulse signal into electro-optical modulator, and continuous laser output from the tunable laser passed through the modulator and was modulated into a light pulse. An isolator is used to prevent unwanted feedback into the laser source and modulator as well. The modulated pulses are coupled into the fiber loop via one arm of Coupler1 and passed through the fiber loop. In addition, the electromagnetic coil with water-cooling is applied in the system to provide stable external magnetic field, and Gauss meter is utilized to detect the magnetic field where the magnetic field sensor stay. Periodic trains of decayed pulses are then coupled out of the fiber loop by one arm of Coupler2. The output periodic trains of pulses are detected by a photo-detector and eventually displayed on an oscilloscope.

2.3.2. Measurement principle

When light propagated in the core of fiber in the sensing head, it is reflected from the interface of its core and cladding by total inner reflection. One part of the light propagates in the fiber core, while the other part of light, called evanescent wave penetrated through the cladding, traveled parallel to the interface along its axis and attenuated along its radial direction quickly [24]. And the mode field diameter of single-mode fiber is about 10.4 μm with light source at 1550 nm. Thus, the evanescent wave can leak into the external medium MF by etching the cladding of single-mode fiber. And the leakage increases with the reduction of the