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[INVITED] Magnetic field vector sensor by a nonadiabatic tapered Hi-Bi fiber and ferrofluid nanoparticles ☆

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ABSTRACT

A magnetic field vector sensor based on super-paramagnetic fluid and tapered Hi-Bi fiber (THB) in fiber loop mirror (FLM) is proposed. A two-dimensional detection of external magnetic field (EMF) is experimentally demonstrated and theoretically simulated by Jones matrix to analyze the physical operation in detail. A birefringence is obtained due to magnetic fluid (MF) in applied EMF. By surrounding the THB with MF, a tunable birefringence of MF affect the transmission of the sensor. Slow and fast axes of this obtained birefringence are determined by the direction of applied EMF. In this way, the transmission response of the sensor is depended on the angle between the EMF orientation and the main axes of polarization maintaining fiber (PMF) in FLM. The wavelength shift and intensity shift versus EMF orientation show a sinusoidal behavior, while the applied EMF is constant. Also, the changes in the intensity of EMF in a certain direction results in wavelength shift in the sensor spectrum. The maximum wavelength sensitivity of 214 pm/mT is observed.

1. Introduction

Magnetic fluid (MF) is a kind of stable colloidal suspension system included surfactant-coated magnetic nanoparticles with sizes around 5–10 nm dispersed in an appropriate liquid carrier. MF has both the features of magnetic property of solid magnetic materials and fluidity of liquids, which makes it an attractive material. Magnetism controllability of MF nanoparticles is unique characteristic that has attracted a lot of attention [1]. In an applied external magnetic field (EMF), these nanoparticles make nano-chain clusters. The length and direction of these clusters depend on EMF strength and direction, respectively. This presents a series of magneto-optic properties, including tunable transmission loss, tunable refractive index (RI), and tunable birefringence [2–6], which help development of numerous photonic devices such as optical switches, optical modulators and optical magnetic sensors [7–12].

Magnetic sensors are important in many industries like an intelligent transportation and electric power transmission. So far, some optical magnetic sensors based on MF have been designed by surrounding the MF in circumambient a fiber optic sensor as a cladding layer [13–15] or by filling the photonic crystal fibers (PCFs) [16,17]. The evanescent field coupling effect is the base of tunable RI and tunable transmission loss of MF-based optical magnetic sensors. This effect results in high sensitivity of these sensors.

Most of MF-based magnetic sensors are only sensitive to the EMF strength and few of them are sensitive to both EMF strength and its direction as a vector-based sensor. Anisotropic aggregation of MF around a fiber optic sensor and coupling with evanescent effect is the principle of sensing mechanism of these sensors. Two-dimensional (2D) EMF vector sensors have been demonstrated by using tilted fiber Bragg grating (TFBG) [18], plasmonic TFBG [19], MF-filled PCF [20], MF-filled microstructured polymer optical fiber [2], and tapered multi-core fiber optic [21]. Also, three-dimensional (3D) EMF sensor have been investigated by sandwiching a thin core fiber (TCF) between two single mode fibers (SMFs) [22].

However, until now, the effect of obtained birefringence of MF nanoparticles on high birefringence fiber and also on the polarization of light has not been studied. For this purpose, a Fiber loop mirror (FLM) is suggested. FLMs are attractive devices to be employed as sensing applications [23,24]. In this system, all of the light beams can reflect back to the input port. But, by inserting a high birefringence (HB) fiber inside of the FLM, some part of light can transmit to the output port. Since FLM with HB is independent of input light polarization and has high extinction ratio, it has attracted a lot of attention. Since traditional FLM do not sense an

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external RI, tapering the fiber optic is necessary to make the evanescent field of the propagation light in the HB exposed to external environment [6]. A non-adiabatic tapered HB fiber (THB) in FLM has the advantages of simultaneous measurement of EMF strength and temperature [25], simultaneous measurement of RI of MF and temperature [23], measurement of the birefringence of MF, and obtaining the direction of EMF.

In this work, a THB in a FLM structure was used to induce the strong evanescent field as an EMF sensor with the advantage of obtaining the direction of EMF. The EMF direction is detected in 2D space. Based on the anisotropic distribution of MF nanoparticles around the fiber, an approach of fabricating a MF-based fiber-optic vector magnetometer is presented. A theoretical simulation of the sensor configuration is done by Jones matrix analysis of the sensor structure and birefringence effect of the MF. Also, this sensor can be used for EMF 3D direction and strength detection. Moreover, birefringence effect of the MF can be studied and measured.

2. Theoretical model and analysis

2.1. Effect of magnetism anisotropy of magnetic nanoparticles

The anisotropic chain-like aggregation of MF nanoparticles surrounding the fiber optic is the base of the interaction of light and MF that leads to photonic properties such as direction dependent RI, birefringence, and transmission loss. The mechanism of anisotropic aggregation of MF surrounding a fiber optic was studied by an air-bubble in a MF film [2,19–22]. It shows that anisotropic aggregation of MF alters in a 3D EMF. From a microscopic point of view, MF nanoparticles are suspended in a carrier solvent to form a colloidal fluid. By applying EMF, magnetic dipole of MF nanoparticles is rapidly aligned by EMF direction. Nanochain clusters are the result of dipolar interactions of MF in EMF. However, a fiber surface causes a small fluid discontinuity and rearranging of the clusters. The nanoparticles are attracted to the parallel surface to EMF, and in greater numbers with increasing EMF. As seen in Fig. 1, the potential energy of applied EMF makes a new equilibrium that leads to the anisotropic distribution of MF nanoparticles surrounding the fiber optic. The concentration of nanoparticles on the lateral edges of fiber optic in the parallel to EMF direction is larger than perpendicular to EMF direction, on the top and down edges of fiber optic, as seen in Fig. 1(I). This phenomenon cause asymmetry of mode profile of nonadiabatic tapered optical fiber (NATOF). In Fig. 1, by assuming the fiber optic is along Z-axis and EMF is perpendicular to the fiber, MF nanoparticles surrounding the fiber optic are in the X-Y plane, according to the cross-section of the fiber. As illustrated in Fig. 1, by applying EMF, the MF nanoparticles aggregate and make nanochain-clusters in the parallel direction to EMF. It can be seen that nanochain-clusters create anisotropic distribution such that it can change the uniformity of electronic field profile of fiber and convert the fiber as a polarizer with birefringence effect. The fast axis and slow axis of the fiber optic can be controlled by EMF strength and direction changing.

Without considering the fast and slow axes of PANDA fiber optic (Fig. 1), the nanochain of nanoparticles induce an extra fast and slow axes in THB. These fast and slow axes are in the parallel to EMF direction and perpendicular to EMF direction, respectively. The amount of the MF birefringence can be controlled by density distribution of nanochain-clusters as a result of changes in EMF strength.

The magnetic-controllable aggregation of the MF nanoparticles surrounding the THB generates a tunable RI and geometrical birefringence. Based on the evanescent field coupling effect, the RI of optical modes in the fiber can be locally modified by surrounding MF nanochain-clusters.

A polarization-maintaining optical fiber (PMF) is a birefringence due to asymmetry in PMF fiber optic structure. Also, its optical modes are asymmetric. By tapering PMF fiber optic, this fiber can be sensitive to the surrounding environment as a result of evanescent field effect. Therefore, the locally geometrical birefringence of PANDA fiber covered by MF nanoparticles can be externally controlled by applying EMF in different directions and various strengths.

2.2. Theory of experimental setup

The sensing mechanism is primarily based on the tunable RI modification of cladding mode of a THB in a FLM (THB-FLM), which is influenced by the magnetism of nanochain-like aggregation of MF surrounding the NATOF. The spectrum of THB shows the wavelength shift and transmission intensity changing (loss) with changing the direction and intensity of EMF.

By tapering a small length of a HB fiber, the extra lengths of HB fiber remain on both sides of THB. In this way, THB is sandwiched between two parts of HB. Fig. 2 shows schematically the configuration of a THB such that a NATOF made of HB is sandwiched between two parts of HB with the name of HB_1 and HB_3, while NATOF is surrounded by MF. As seen in Fig. 2(a), the light beam arrives in the 3 dB coupler from port 1 and propagates in clockwise (CW) and counter-clockwise (CCW) through port 3 and 4, respectively, and transmits and reflects from ports 2 and 1, respectively. By applying EMF (perpendicular) to the THB fiber, MF nanoparticles make nanochain-clusters surrounding the THB and locally affect the birefringence of the THB. Therefore, it can be assumed that a THB surrounded by MF (Taper-MF or THB-MF) exposed to EMF works like a NATOF plus HB_2, as shown in Fig. 2(b). The strength and direction of EMF affect the RI of optical modes of NATOF and locally geometrical birefringence of HB_2, respectively. The locally geometrical birefringence of HB_2 is impacted by the rotation angles of θ_2 and θ_3 which are relative angles of the state of polarization (SOP) of HB_1 to HB_2 and HB_3 to HB_2, respectively. θ_1 and θ_4 denote the rotation angle of the SOP with respect to the laboratory coordinate system. Since the tapered region is made on a HB fiber by heat and pulling method using a CO_2 laser as

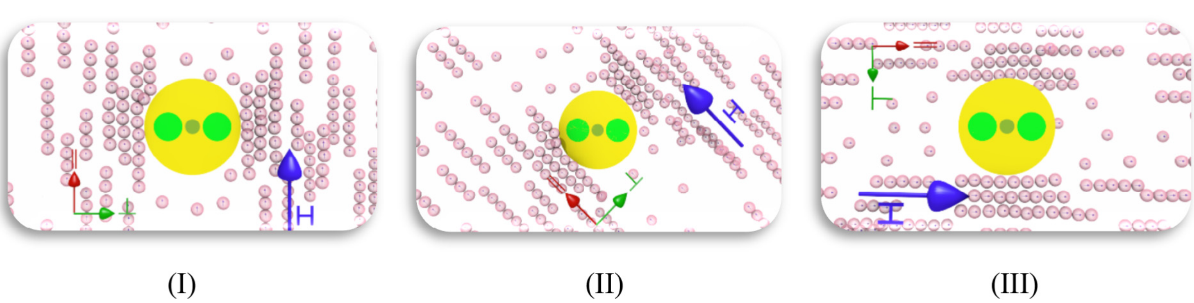

Fig. 1. Schematically orientation of MF nanoparticles surrounding a typical tapered Hi-Bi fiber (THB) in different EMF directions.