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Design of a Magnetic-Sensor Based on Fe_3O_4 Nanofluid Infiltration

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Abstract

A magnetic sensor, using a Hollow core-photonic crystal fiber infiltrated by a small amount of a magnetic nanofluid Fe_3O_4, is designed. The optical properties of this kind of fiber and the relation between the magnetic field and the magnetic nanofluid are employed to build the sensor. Laser light with the wavelength 674 nm is used to conduct the setup. A linear response in the wavelength-shift, of the transmitted spectrum corresponding to the applied magnetic field, is obtained. The wavelength-shift maintains its linearity throughout a range of magnetic field (0-245) Oe. The magnetic sensor shows a significant sensitivity about 19.03×10^{-12} m/Oe.

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1. Introduction

Magnetic-field sensors are employed in a wide range of applications, including navigation, speed and distance measurements, geophysical research, noncontact switching, and current measurement [1]. The field of magnetic sensors has seen rapid progress, Wang *et al* [2] demonstrated a magnetic sensor based on dual-core PCF. Chen *et al* [3] formed a sensor based on anisotropic of magnetic fluid (MF) particles. A Mach-Zehnder Interferometer (MZI) fiber was coated with MF to build a sensor[4]. Moreover, some sensors are designed using traditional fibers such as Single mode (SM) and Multimode (MM) forming SMS structure by splicing the MM fiber between two SM fibers [5-7]. In this work, the sensor is based on the injected magnetic fluid into the core and holes of the Hollow-Core Photonic Crystal Fiber (HC-PCF). The formula below gives the transmitted intensity of the light passing through the PCF with length L [8, 9],

$$I(L) = \frac{\left|\int_0^{\infty} E(r,0)E(r,L)rdr\right|^2}{\int_0^{\infty}|E(r,L)|^2 rdr \int_0^{\infty}|E(r,0)|^2 rdr} \quad (1)$$

where r is the radial coordinate of the cross-section of the fiber and $E(r,0)$ indicates the field of the incident of the input light given by [6],

$$E(r,0) = \sum_{m=1}^{M} C_m \Psi_m(r) \quad (2)$$

where C_m is the excitation coefficient, M is the number of the modes, $\Psi_m(r)$ denote the field profile of the mode and, $E(r,L)$ represents the electric field of the output light given by [6],

$$E(r,L) = \sum_{m=1}^{M} C_m \Psi_m(r) \exp(-\alpha_m L) \exp(j\beta_m L) \quad (3)$$

Both α_m and β_m denote the absorption (or attenuation) and propagation coefficients for the m^{th} mode of the PCF, respectively [6,8,9].

Under applying a magnetic field, and due to the interaction between the MF and the magnetic field, the particles of the MF will be magnetized. The magnetic dipoles will be aligned in parallel relative to the applied field direction. Therefore, the particles start to agglomerate along their direction forming magnetic columns or chain-like structures leading to a phase-separation [10]. The dynamics of magnetic dipoles will affect the dielectric constant, which perturb the refractive index. Theoretically, the tunable refractive index (n_{MF}) is given as [8] ,

$$n_{MF} = \sqrt{\varepsilon_{MF}} \quad (4)$$

The effective dielectric constant (ε_{MF}) depends on the dielectric constants of the MF and the columns of the nanoparticles. Although the dielectric constant of the MF changes, due to the variety in the applied field, the dielectric constant of the columns stays constant. Therefore, the changing magnetic field will affect the refractive index and both α_m and β_m. Such insight can be deduced from Eq. (4). This affection interprets how the refractive index of the fluid responses and is tuned magnetically.

2. Experimental Work

The magnetic-optical responses such as Faraday induction, the change of the refractive index under the change of the external effect, the birefringence, the absorption coefficient, monochrome and dichroism, are manifested in the study of the magnetic fluids [11,12]. The early designs of magnetic sensors included magnetic substances such as a thin film of iron or partly crystalline film of (TbDyFe) [4,13]. Later, the advantages of the ferromagnetic nanoparticles of iron oxid attracted the researchers to use it in the optical fiber sensors [14]. The liquid state of Fe_3O_4 is more feasible, compared to other optical materials, to be injected in the PCF sensors. Thus, Fe_3O_4 water-based with a concentration of 0.6 mg/ml, and the nominal size of the particles around 10 nm is used in the present work. The MF can be dispersed in other solutions such as kerosene, heptane and dextran to give a different range of the RI [15]. Water is a suitable dispersant since its refractive index (1.333) is lower than the RI of silica (1.45) [16].

The system consists of a light source, which is directed towards the PCF. The wavelength of the light is 674 nm. HC-1550-19-PCF, with 9 cm in length, from (NKT Photonics) is used in this experiment. The core and air-hole diameter is 20 µm, 4.125 µm, respectively, and the pitch is 3.8 µm. The cross-section of the PCF structure is shown in Figure (1). A spectrometer (200-1160 nm, AvaSpec-ULS2048XL) is used to detect the transmitted spectrum passing through the PCF. The power supply is used to adjust the current of a solenoid coil with 300 turns, which leads to a uniform magnetic field intensity (H) that ranges (0-245) Oe inside the coil. A Tesla-meter from (LEYBOLD DIDACTIC GMBH) is used to identify the field intensity. The change of the applied field results in a change in the refractive index of the nanofluid in the PCF. The relation between the RI of the Fe_3O_4 fluid and the applied field has been clarified previously [2,16,17]. The experiment is done in the laboratory at room temperature (25 °C).

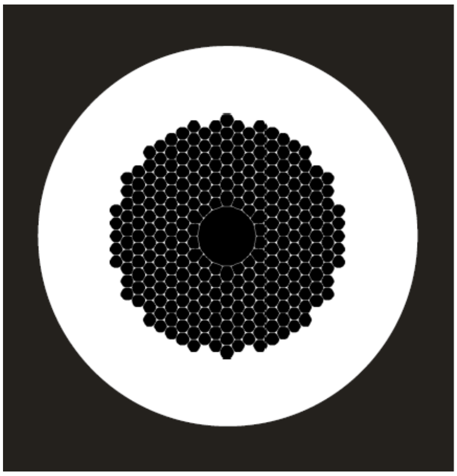
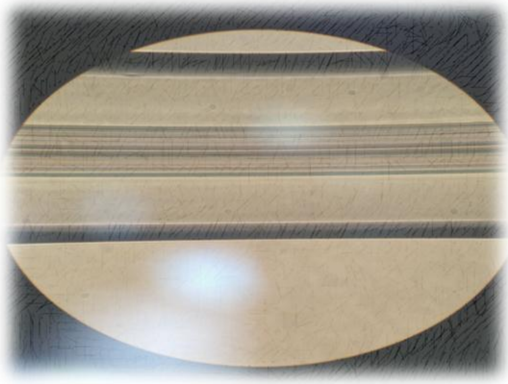
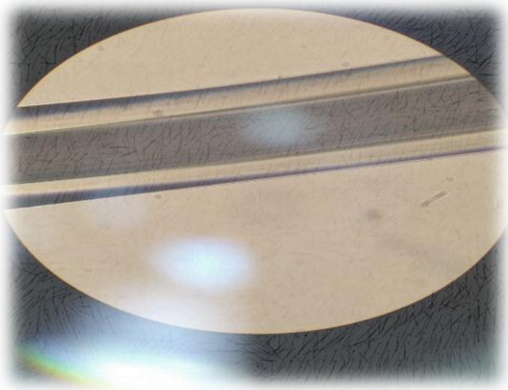


Figure 1. The cross-section of the Hollow-core photonic crystal fiber (HC19-1550-PCF).



(a)



(b)

Figure 2. Microscope images of HC-PCF: (a) Empty HC-PCF fiber. (b) Filled HC- PCF fiber with Fe_3O_4.

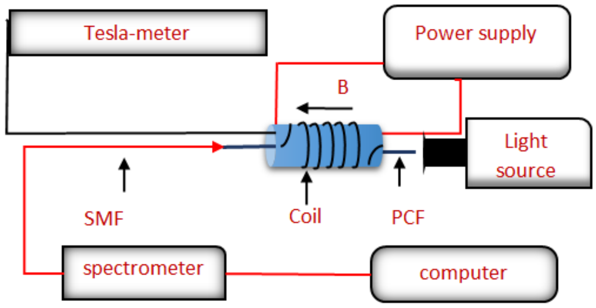


Figure 3. The schematic version of the experiment.

3. Result and Discussion

In the present work, the PCF sensor is placed inside the coil. One side of the PCF is faced to the light source, and the other side is connected mechanically to the single-mode fiber of the spectrometer. The PCF infiltrated with the magnetic fluid using capillary force. Figure 2 depicts the microscopic image of the empty and filled PCF, which confirms that the MF is infiltrated in the core and holes of the PCF successfully. The structure of the experiment is presented in Figure 3.

Figure 4 shows the variation of transmission spectrum intensity and the wavelength shift before and after the injection the MF into the PCF. The wavelength of the transmitted spectrum shifts by 4.5 nm from 674.9 nm to 670.4 nm, according to presence the MF. Before the infiltration of the PCF with MF, a little attenuation and a high value of spectrum intensity was obtained in the empty PCF, due to the high contrast between the refractive indexes of the air and silica. However, after the infiltration of the PCF, a value of the spectrum intensity was decreased due to the high absorption (α_m) of the MF. Thought the experimental work, the measurements are recorded whenever a non-fluctuating spectrum is obtained.

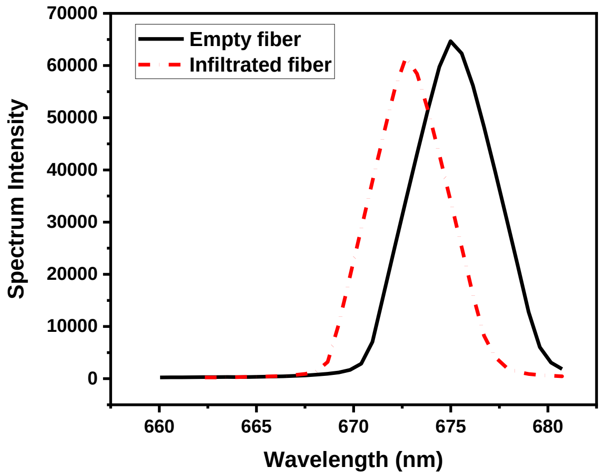


Figure 4. The transmission spectrum of the HC-PCF before (solid black curve) and after (dashed red curve) the infiltration of the magnetic fluid.

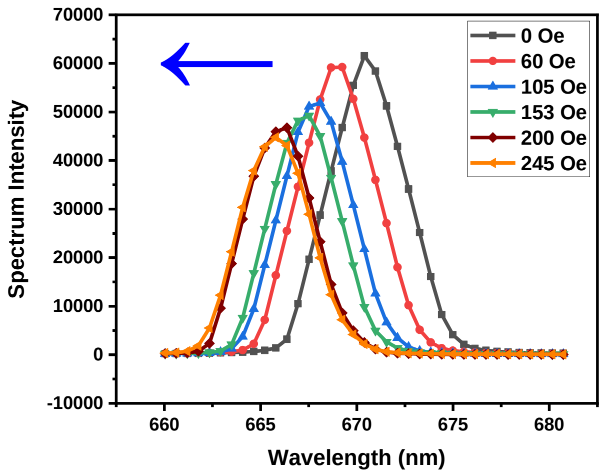


Figure 5. The transmission spectrum of the HC19-1550-PCF injected with 0.6 mg/ml concentration of Fe_3O_4 at various values of the magnetic field.

The relationship between the nanofluid inside the fiber and the applied field is considered. The applied field was changed from 0 Oe to 245 Oe. Figure 5 illustrates that the intensity attenuation increases as the magnetic field increases. Applying the magnetic field, results in an agglomeration of the MF particles. In fact, those particles start to form a phase separation which causes a variation in the ε_{MF}. The variation has the ability to change the RI of the MF according to the Eq. (4). Additionally, the increase in the α_m of the magnetic fluid and β_m of the PCF cladding, leads to a decrease in the intensity of the spectrum through the core. The peak-shift of the transmission spectrum demonstrated in Figure 5, agrees with the theoretical implications of Eq. (4). The blue arrow, in Figure 5, represents the direction of the shift, which is caused by the increase in the magnetic field.

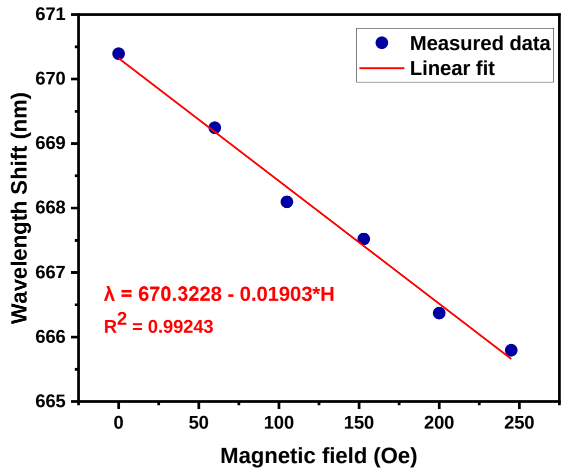


Figure 6. The relation between the wavelength peak-shift respecting to the magnetic field intensity (H).

Figure 6 shows the relation between the wavelength-shift (or the center of the wavelength) and the field intensity. The wavelength-shift decreases with the change in the field intensity to high values (0 Oe to 245 Oe). The blue shift in the wavelength and the loss in the intensity of the transmitted spectrum, respectively, produced by the agglomeration in the particles of the MF [11]. In turn, it will form a chain-like cluster affected by the magnetic field [18]. The results depict the linear response of the wavelength-shift as a result of the change in the magnetic field. The fitting coefficient of the linear equation is R^2 = 0.992, and the high sensitivity is 19.03×10^{-12} m/Oe. Oe refers to the unit of the magnetic field strength. The power loss and the blue shift in the spectrum explain the effectiveness of the magnetic field on the MF. In fact, the results confirm the significant characteristics of the MF as a principal ingredient of the sensor.

4. Conclusions

This research demonstrates a magnetic sensor based on a hollow-core PCF infiltrated with a ferromagnetic nanofluid Fe_3O_4. Under the rise of the magnetic field, there is an attenuation in the intensity of the transmitted spectrum. The attenuation is caused by the Fe_3O_4 particles' agglomeration. A shift in the wavelength value, where the peak occurs, is achieved as a result of the tunability of the n_{MF} and α_m of the MF in the PCF. A linear response in the wavelength-shift of the transmitted spectrum corresponding to the applied field is obtained. The wavelength shift maintains its linearity throughout a range of magnetic fields (0- 245) Oe. The magnetic sensor shows a significant sensitivity. The measured magnetic field sensitivity is 19.03×10^{-12} m/Oe, which agrees with the published work. The sensor's design is simple in fabrication, low in cost and small in content and size.

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