Magneto-optical sensor based on the bandgap effect of a hollow-core photonic crystal fiber injected with Fe₃O₄

R A Aobaid¹ and H S Hussain

Department of Physics, College of Science, Al-Nahrain University, Baghdad, Iraq
E-mail: rowida.obaid@gmail.com

Abstract. A magnetic field sensor, using a hollow-core photonic crystal fiber (HC-PCF), based on the bandgap effect was designed and experimentally demonstrated. The water-based Fe₃O₄ was infiltrated into the core and the holes of the HC-PCF. The magnetic fluid was prepared with a concentration of 0.6mg/ml. A diode laser with a wavelength 532nm was used as a light source. Two types of HC-PCF were used: HC-1550-19 PCF and HC-800-02 PCF. The sensitivity was tested for a magnetic field that ranges from 0 mT to 24.5 mT. The results demonstrate that the sensitivity of the proposed sensors was 119.95 pm/mT and 151.27 pm/mT for HC-800-02 PCF and HC19-1550 PCF, respectively.

1. Introduction
The last few decades have seen the invention of a new class of optical fibers which is called the photonic crystal fiber (PCF). This achievement occurred after the reengineering of the microstructure of the conventional optical fiber. PCF contains a network of capillaries filled with air, along its length to form a fixed lattice structure. PCF combines the properties of conventional fibers and photonic crystal such as their ability to detect any environmental change on the photonic crystal, which causes a shift in the provided modes (For instance, elongation of the crystal will change the periodicity and will cause modes-shift). Therefore, they possess unique properties such as endlessly single-mode transmission, high birefringence, large nonlinear coefficient, flexible dispersion management. PCFs are made up of pure silica. PCFs are widely used in many applications, such as fiber lasers, optical communications and optical devices [1]. A significant application of PCFs is the fiber sensors. Filling the air-holes of the PCFs can make them an excellent candidate as an optical sensor with ultra-high sensitivity [2]. For instance, Thakur et al. demonstrated a magnetic field sensor, based on a magnetic fluid infiltrated into the air-holes of a polarization-maintaining photonic crystal fiber (PM-PCF), with a high sensitivity of 242 pm/mT [3]. Candiani et al. presented a magnetic field controlled phase-shifted fiber grating by filling magnetic fluid into the air-holes in the cladding of a hollow-core PCF [4]. Feng et al. demonstrated a magnetic sensor based on a temperature-independent fiber-optic covered with water-glycerol solutions [5]. Li et al. demonstrated a magnetic field sensor based on surface plasma resonance (SPR) optical fiber filled with magnetic fluid into the capillary sealed with epoxy glue [6]. Several magnetic field sensors were designed using a magnetic fluid film in optical fiber interferometers, such as Sagnac (Fabry-Perot) interferometer [7] and Mach–Zehnder interferometer [8]. A significant number of magneto-optical modulators were carried out by using the magnetic fluid as the outer cladding of tapered or etched fibers [9,10].

2. Photonic bandgap effect
The technique of filling the holes of the PCF, which results in modifying the fiber’s properties, has
seen a significant interest in many fields. Gases, metals, and liquids are used as a filler material [11–13]. PCFs are classified into two kinds: solid core photonic crystal fiber (SC-PCF) and hollow core photonic crystal fiber (HC-PCF). It is well known that the light can be guided within the core of the PCF by two methods: total internal reflection (TIR) for SC-PCF, where the core has a refractive index higher than the cladding, and photonic bandgap (PBG) for HC-PCF, where the core has a refractive index lower than the cladding [14]. The mechanism of guiding light in the PCF can be converted from the PBG bandgap guiding to the total internal reflection by filling the core and the air-holes of the HC-PCF by a magnetic fluid with a refractive index higher than 1.45. Changing the properties of the filling material, which is a significant feature of the HC-PCF, results in changing the bandgap of the PCF. For instance, changing the refractive index of the filling material, which effect the effective refractive index between the cladding and the core, causes a change in the bandgap, which guides the light inside the HC-PCF. The changed bandgap effect can be used to develop a high sensitive of the PCF sensors.

The magnetic fluid Fe₃O₄ water-based is the most commonly used in magneto-optical sensors. Because the magnetic fluid is a superparamagnetic material, which means the magnetic fluid always returns to its original state when the applied magnetic field is removed. At zero magnetic field, the nanoparticles of the magnetic fluid will disperse homogeneously in the solution, which is a mono-dispersion state. When the magnetic field is present, the nanoparticles begin to agglomerate to form magnetic columns in a polarization form. Simultaneously, phase separation occurs between the stable nanoparticles and the liquid solution [15,16]. The change in the dispersion state of the nanoparticles subsequently affects the refractive index of the magnetic fluid, which affects the bandgap of the HC-PCF. Under the zero magnetic field, the refractive index of magnetic fluid depends on the concentration of the liquid solution, where the refractive index increases linearly with the particle concentration of Fe₃O₄ [17]. As the applied magnetic field strength increases, the refractive index of the magnetic fluid increases slightly at specific concentration. At high concentrations, the magnetic fluid can show a wide range of refractive index before reaching a saturation value [18]. The change in the refractive index of the magnetic fluid, as a result of tuning the applied magnetic field, can be employed in the magnetic field sensing applications. A high degree of sensitivity can be obtained as long as a significant variance of the refractive index of magnetic fluid was achieved.

3. Sensor design and discussion

For comparison, two different types of the PCF with the same length (9 cm) were used in this experiment: HC-800-02-PCF and HC19-1550-PCF, from (NKT Photonics). Figure 1 depicts a hollow core surrounded by a microstructure cladding of air holes and silica in the cross-section of the (a) HC-800-02 PCF, (b) HC19-1550 PCF, respectively. The core diameter, air-hole diameter, and pitch for HC-800-02 PCF are 7.5 µm, 2.812 µm, and 2.3µm, respectively. Fore HC19-1550 PCF, the core diameter, air-hole diameter, and pitch are 20 µm, 4.125 µm, 3.8 µm, respectively. The various guiding properties of a PCF can also be tuned by varying the structural parameters of the PCF [19]. In the present work, the water-based Fe₃O₄ with nominal sizes about 10 nm was prepared with a concentration of 0.6 mg/ml. The refractive index of the magnetic fluid was lower than 1.45 since the refractive index of the water is only 1.333 [20]. The magnetic fluid has been filled successfully in the core and the holes of both PCFs based on the capillary phenomena at room temperature. Figure 2 demonstrates the microscope images of the empty and filling fiber.
Figure 1. The Schematic cross-section of the Hollow Core Photonic Crystal Fiber: (a) HC-800-02 PCF. (b) HC19-1550 PCF.

Figure 2. Microscope images of HC-PCF: (a) Empty HC-PCF fiber. (b) Filled HC-PCF fiber with Fe₃O₄.
The magnetic sensor structure is shown in Figure 3. In the experiment, the current of the power supply was adjusted to make the magnetic field ranges from 0 mT to 24.5 mT. The Tesla-meter from (LEYBOLD DIDACTIC GMBH) was used to measure the magnetic field. A spectrometer (200–1160 nm, AvaSpec-ULS2048XL) was employed to monitor the transmission spectrum passed through the HC-PCFs. The operating wavelength was 532nm.

![Figure 3. Experimental setup of the magnetic field sensor.](image)

The change in the bandgap of the PCFs according to the change in the magnetic field, as a result to the change in the refractive index of the magnetic fluid, is tested by analysing the spectrum intensity of the wavelength. Figure 4 illustrates the spectrum intensity amplitude decreases when the magnetic field increases. Interpretation of this, the increased refractive index, according to the increased magnetic field, caused an increase in the attenuation and absorption parameters of the magnetic fluid. Moreover, the increased refractive index of the magnetic fluid (MF) caused a decrease in the effective refractive index between the core and cladding, which lead to a transition loss in the cladding. Figure 4 (a) indicates that the peak- shift for HC-800-02 PCF decreased to a lower value (34515.11). In the case of HC19-1550 PCF as shown in Figure 4 (b), the value declined to (37488.11). The findings indicate that the light confinement is significantly affected by the size of the core.

Figure 5 shows the relationship between the magnetic field versus the wavelength. The figure indicates that the wavelength, at which the peak of the intensity occurred, shifted quickly and linearly towards the short wavelengths region as a result of the increase in the applied field. Figure 5(a) shows a low response of the magnetic fluid when the magnetic field is changed from 6 mT to 15 mT. This is caused by the agglomeration of the magnetic particles. Figure 5(b) shows that the response of the MF to the magnetic field starts after 6 mT. A linear equation was found to predict the shift in the wavelength, as shown in figure 5. The high goodness-of-fit coefficient $R^2$ values, 0.92 (for HC- 800-02) and 0.98 (for HC19-1550), indicate the quality of the fitting equation. The sensitivity was obtained from the fitting equation in figure 5. The sensitivity of (HC-800-02) was 119.95 pm/mT whereas the sensitivity of (HC19-1550) was 151.27 pm/mT.
4. Conclusion

In summary, a magnetic field sensor based on the tuneable bandgap effect of the PCF filled with magnetic fluid was designed. The work has demonstrated that there was a quasi-linear response of the wavelength shift as a result to the change in the magnetic field. The wavelength shifted quickly and linearly towards the short wavelengths region with respect to the increase in the applied field. In fact, increasing the magnetic field affected the effective refractive index between the core and cladding indexes, which led to a change in the bandgap. Moreover, the work has indicated the effect of the structural parameters of the PCFs, such as the pitch, the core and the hole diameters, on the attenuation and confinement of the light. The achieved sensitivities of the sensor were 119.95 pm/mT and 151.27 pm/mT for HC-800-02 PCF and HC19-1550 PCF, respectively. A level of improvement had been added to the sensitivity of the sensor using the HC19-1550 PCF. The main advantages of the proposed sensor were its asimple design, the low cost and the small size.
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