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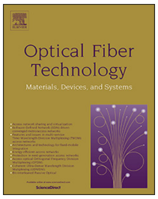

Analysis of a magnetic field sensor based on photonic crystal fiber selectively infiltrated with magnetic fluids

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ABSTRACT

A magnetic field sensor based on magnetic fluids (MFs) selectively infilling photonic crystal fiber (PCF) is designed and analyzed by the finite-element method (FEM). The PCF consists of three-layer air holes in the cladding which are arranged in regular hexagonal lattice. The left and right sides of the fiber core are made up of two larger circular air holes while the upper and below sides are made up of four smaller circular air holes which are benefit to enhance the birefringent effect. MFs are injected into one air hole in the second cladding layer which generates a defect core with high confinement loss. Air holes around the defect core are asymmetrically distributed which can enhance the birefringence of the transmission mode in defect core. When the phase matching condition between core modes and defect core modes is satisfied, the light transmitting in the core couples to the defect core and a sharp decrease of light transmitting energy occurs. The refractive index of defect core modes is modulated by magnetic field strength. The peak wavelengths of confinement loss spectra depicts pretty well linear relationship with magnetic field strength in the detected range of 30–130 Oe. The magnetic field measuring sensitivity reaches to 584 pm/Oe for x-polarized mode and 700 pm/Oe for y-polarized mode, respectively.

1. Introduction

MFs, which have both the liquidity of liquids and the magnetic property of solid magnetic materials, are consisted of magnetic nanoparticles, liquid carrier and surfactant [1]. Due to the fascinating properties in magnetics, optics and electronics such as Faraday effect, birefringence effect and dichroism, MFs have attracted a lot of interests of scholars and engineers [2–5]. In the detecting of magnetic field strength, Lei, Xueqin, et al. reported a MFs-filled D-shaped fiber magnetic field sensor based on Sagnac interferometer whose sensitivity was 0.0823 nm/mT [6]. Tang, J., et al. reported a magnetic field sensor based on a MFs-clad multimode-singlemode-multimode fiber structure in which the magnetic field sensing sensitivities of 60.5 pm/mT and 0.4821 dB/mT were obtained [7]. A compact all-fiber magnetic field sensor is achieved by using Mach–Zehnder interferometer based on hollow optical fiber (HOF) and MFs. A maximum magnetic field sensing sensitivity of −170 pm/Oe was obtained [8].

PCF in which the air holes are arranged evenly in the cladding, has been infiltrated with various functional materials to achieve different optical devices [9,10]. MFs is a kind of functional material in magnetics. When the concentration of magnetic particles in MFs and the carrier fluid are fixed, the refractive index of the MFs changes significantly with magnetic field and temperature. The combination of PCF and MFs provides a way to study new magneto-optical devices. More and more scholars have infiltrated the PCF with MFs as an optical device for measuring magnetic field strength and temperature. A Mach-Zehnder interferometric magnetic field sensor based on a PCF and MFs was designed by Yang, Hang Zhou, et al. The results showed that the sensitivity of the proposed sensor can reach to −0.13 dB/mT and 0.07334 nm/mT in the magnetic field intensity range of 1–20 mT and 2–20 mT, respectively [11]. Li proposed a magnetic field sensor based on a dual-core PCF which is formed by filling MFs in two air holes and the sensitivity was 4.8 pm/Oe [12]. Zhao, Yong, et al. studied the MFs filled hollow-core PCF and the sensitivity was about 33 pm/Oe based on the proposed sensor [13]. Gangwar, et al. reported the modeling result of magnetic field sensor based on MFs selectively infiltrated dual-core PCF and the sensitivity of 172.54 pm/Oe was achieved [14]. Hl Chen, et al. proposed a magnetic field sensor based on MFs infilling PCF and the maximum sensitivity can reach to 542.9 pm/Oe. However, the result showed that the peak wavelengths was not linearly related to the magnetic field intensity which affected its use in practical [15].

In this paper, a magnetic field sensor based on PCF and MFs is

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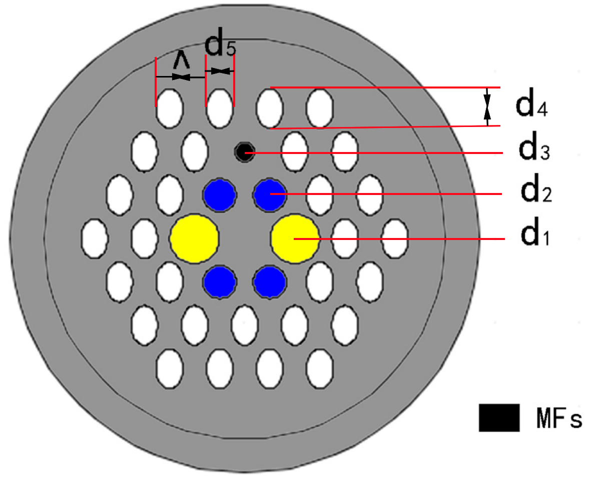

Fig. 1. Cross-section of the PCF. Structure parameters are $d_1 = 3.2\,\mu m$, $d_2 = 2.0\,\mu m$, $d_3 = 1.2\,\mu m$, $d_4 = 2.4\,\mu m$, $= 1.6\,\mu m$ and $\Lambda = 3\,\mu m$.

proposed. We analyze through FEM by using COMSOL Multiphysics software. One air hole in the second cladding layer of PCF is infiltrated with MFs to form a defect core. The asymmetric design of the fiber core and defect core enhances the birefringence of the transmitting modes. The simulation results show that the designed magnetic field sensor has a high sensitivity of 580 pm/Oe in the range of 30–130 Oe. The wavelength of loss peaks and the magnetic field intensity shows a perfect linear relationship. Both high sensitivity and good linearity are major advantages of this magnetic sensor. Finally, the performance characteristics can be enhanced further by optimizing the configuration parameters.

2. PCF structure and operation principle

The cross section of the proposed magnetic field sensor based on MFs selectively infilling PCF is shown in Fig. 1. The fiber core is formed by removing the central air hole. The cladding of the PCF is composed of circlar holes and elliptical holes in a regular hexagonal lattice. The lattice pitch is represented by Λ. The diameters of yellow air holes, blue air holes and black air hole are represented by d_1, d_2 and , respectively. The long axis and short axis of the ellipses are represented by d_4 and d_5. The main purpose of this design is that the structure is not only novel, but also improves the performance of birefringence. The black hole is filled with MFs. In experiment, we can directly use the selective filling method to achieve the selective infilling of MFs in PCF. One of the infilling technology is directly injecting MFs into the air hole by using a micropipette [16]. The background material is pure silica. Its chromatic dispersion can be described by the Sellmeier equation which is defined as

$$n^2(\lambda) = 1 + \sum_{i=1}^{3} \frac{a_i\lambda^2}{\lambda^2 - b_i^2} \tag{1}$$

here λ is the wavelength of light. The parameters are $a_1 = 0.6961663$, $a_2 = 0.4079426$, $a_3 = 0.8974794$, $b_1 = 0.0684043\,\mu m$, $b_2 = 0.1162414\,\mu m$ and $b_3 = 9.896161\,\mu m$ [17]. Thus, the dispersion of PCF transfering modes can be calculated.

The air hole whose diameter is is infiltrated with MFs to be transformed into a defect core. The refractive index of MFs follows Langevin function 18.

$$n_{MF} = [n_m - n_i]\left[coth\left(\alpha\frac{H - H_{c,n}}{T} - \frac{T}{\alpha(H - H_{c,n})}\right)\right] + n_i,\ \ for\ H > H_{c,n} \tag{2}$$

where n_m is the maximum refractive index value that the MFs can achieve. n_i is the original refractive index as external magnetic field strength is lower than $H_{c,n}$. $H_{c,n}$ is the critical magnetic field strength and α is the fitting parameter. n_{MF} is the refractive index of the MFs and changes with external temperature and external magnetic field strength. Fig. 2 shows the refractive index of the MFs various with the external magnetic field strength, when the external temperature is a fixed value. The parameters are $n_i = 1.400$, $n_m = 1.408$, $H_{c,n} = 30$ Oe, $\alpha = 5$ and T = 300 °C. We can see that when external magnetic field strength is less than critical magnetic field strength, the refractive index of the MFs does not change with the external magnetic field strength. The direction of the magnetic field is along the axial direction of the fiber and MFs are magnetized along the axial direction of the fiber. When the magnetic field strength is relatively strong, MFs are gradually magnetized to saturation. The refractive index of MFs also tends to a fixed value.

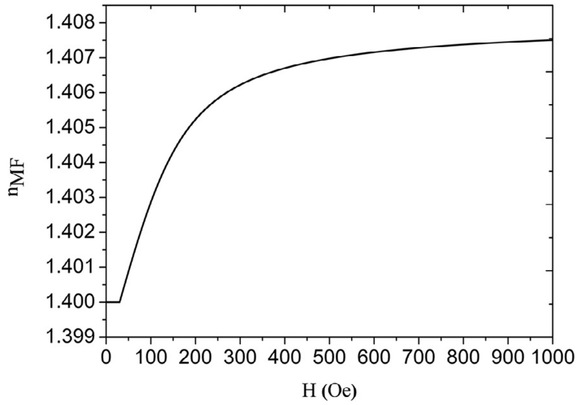

Fig. 2. Relationship between the refractive index of MFs and external magnetic field strength. The parameters of the MFs Langevin function are $n_0 = 1.400$, $n_s = 1.408$, $H_{c,n} = 30$ Oe, $\alpha = 5$ and T = 300 °C.

Coupled-mode theory (CMT) is the fundamental principle that the designed magnetic field sensor complies with when it works. For core and defect modes, the CMT equations was expressed in 19.

$$\frac{dE_1}{dz} = i\beta_1 E_1 + i\kappa E_2 \tag{3}$$

$$\frac{dE_2}{dz} = i\beta_2 E_2 + i\kappa E_1 \tag{4}$$

From the CMT, we can know that the couple of the fiber core and defect core will take place complete coupling or incomplete coupling, as the phase matching condition is satisfied. When $\delta_i > \kappa$, an incomplete coupling will happen. The real parts of β_+ and β_- are equal, the imaginary parts of β_+ and β_- are different. When $\delta_i < \kappa$, an complete coupling will happen. The real parts of β_+ and β_- are different, the imaginary parts of β_+ and β_- are equal [20]. κ is the coupling strength and β is the propagation constant of the coupling mode. δ_i is the average value of the difference between the imaginary part of the propagation constant of core mode and defect core mode.

3. Numerical results and analysis

In this paper, we can find that the real part of the effective refractive index of core modes and defect core modes are equal. Fig. 3 shows that an incomplete coupling takes place at 1.589 μm in x-polarized direction and at 1.741 μm in y-polarized direction respectively, when external magnetic field strength is 30 Oe.

According to the coupling principle, as phase matching condition is satisfied, the energy of incident light in core will experience an abrupt decrease which forms a highest peak in loss. The confinement loss spectra is shown in Fig. 4 at external magnetic field strength of 30 Oe. The confinement losses of core modes increases to 199 dB/m in x-