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Magnetic fluid infiltrated dual core photonic crystal fiber based highly sensitive magnetic field sensor

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ABSTRACT

A very high sensitive magnetic field sensor based on a square lattice dual core photonic crystal fiber (DCPCF) is proposed in this article. The fiber contains two big magnetic fluid (Fe_3O_4) infiltrated holes around the central region and they are forming two separate waveguide with mode coupling. Mode coupling between these two cores is theoretically studied under influence of different magnetic field strength as well as with changing structural parameters. In the further stage a simple magnetic field sensing system is proposed and its sensing performance is investigated considering manufacturing variation possibilities. Numerical simulation result shows that highest sensitivity of 799.07 pm/Oe can be achieved with probe size of fraction of centimetre. This sensing probe can be used in manufacturing high sensitive portable devices including health monitoring instruments.

1. Introduction

The invention of photonic crystal fiber (PCF) by Russell et al. over step index optical fiber was undoubtedly a path breaking step in twenty century fiber optics technology [1]. Charming optical properties of PCF like low confinement loss, high birefringence, endlessly single mode, flexible dispersion characteristics, high nonlinearity etc. strongly depend on its structural parameters [2–6]. These are motivating many research groups in developing advanced PCFs as well as optical devices such as communication devices, PCF sensors, fiber laser, nonlinear devices, supercontinuum generator, optical devices, medical instruments etc. based on these PCFs [7–14]. Among these devices development rate of PCF sensors is very high from last decades. During this period refractive index sensor, temperature sensor, bio sensor, magnetic field sensor, pressure sensor is gathering great interest [15–19]. Combination of selective material infiltration technique with PCF gives a new height to the sensitivity of these sensors due to direct interaction of passing light with analyte [21,22]. Though in past years fiber based magnetic field sensor was mainly developed using fiber Bragg gratings [23], step index fiber combination [24] and micro fiber coupling [25,26] but in recent few years PCF based magnetic field sensors have drawn enough attention of researchers [27]. At early stage, Thakur et al. had reported a polarization-maintaining PCF based magnetic field sensor whose cladding holes are infiltrate with magnetic nanofluid having sensitivity 242 pm/mT [28]. Then Zu et al. demonstrated a collapsed PCF based magnetic sensor with sensitivity 2.367 pm/Oe [29]. At the same time Zhao et al. reported a magnetic fluid filled hollow core photonic crystal fiber magnetic field sensor with sensitivity 33 pm/Oe [30]. A magnetic fluid infiltrated PCF based Mach–Zehnder Interferometer was demonstrated by Gao and Jiang for magnetic field measurement having sensitivity up to 0.042 dB/Oe [31]. Then Qiu et al. had proposed an ampere force based PCF magnetic field sensor with max. sensitivity 32.4 pm/mT at 100 mA electrical current [32]. In next year a magnetic field sensor was designed by Mahmood et al. consisting cylindrical whispering-gallery-mode micro-resonator with sensitivity 110 pm/mT [33].

We authors realised that more investigation can be done in making a highly sensitive PCF based magnetic field sensor over the existing magnetic sensors. In this article we made an original effort to design a highly sensitive simple structured DCPCF base magnetic field sensor without fabrication and infiltration complexity. Two fiber cores of this fiber are filled with magnetic fluid (Fe_3O_4) forming independent waveguides working on mode coupling principle. Detail theoretical investigation is carried out using Finite element method (FEM) based software to visualize coupling length as well as sensitivity variation with changing structural parameters and different applied magnetic fields. According to authors best knowledge it is one of the simplest PCF structure with large dimension circular holes for magnetic fluid infiltration as well as with very high sensitivity 799.07 pm/Oe.

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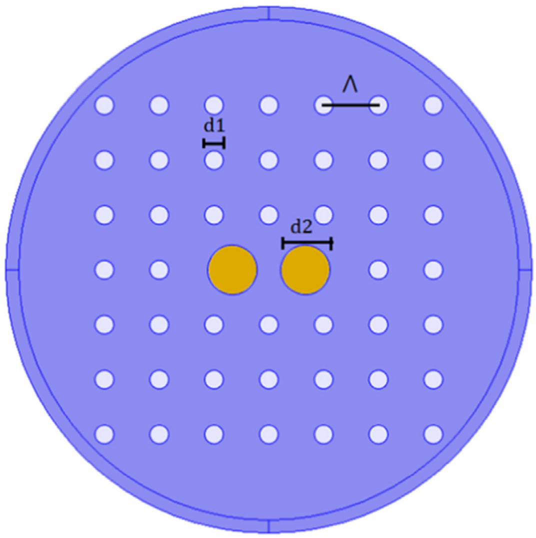

Fig. 1. Cross section of the designed square lattice DCPCF based magnetic field sensor.

2. Geometrical structure and working principle

The cross-sectional view of the proposed square lattice selective magnetic fluid infiltrated DCPCF structure is shown in Fig. 1. We choose square lattice PCF for making a high sensitive sensor instead of popular triangular PCF for its two advanced properties. Firstly, square lattice PCF has lower air-filling fraction which provides higher refractive index of cladding i.e. low step index as a consequence low field confinement. Secondly, square lattice PCF has large effective area and wider coupling channel in comparison to triangular lattice PCF having similar structural parameters [34]. For this square lattice PCF cladding air hole diameter, distance between two successive air holes i.e. pitch and diameter of magnetic liquid infiltrated big holes are denoted by d_1, $\wedge$ and d_2 respectively. As it is a square lattice PCF so adjacent air hole pitches in horizontal and vertical direction are same. The refractive index of air is taken as $n_a = 1$ and background material is fused silica of this PCF. Throughout this simulation, variation of refractive index of silica with changing propagation wavelength i.e. material dispersion of silica is considered by using Sellmeier equation as follows,

$$n^2(\lambda) = 1 + \frac{A_1\lambda^2}{\lambda^2 - B_1} + \frac{A_2\lambda^2}{\lambda^2 - B_2} + \frac{A_3\lambda^2}{\lambda^2 - B_3} \quad (1)$$

Here, Sellmeier coefficients are $A_1 = 0.696166300$, $A_2 = 0.407942600$, $A_3 = 0.897479400$, $B_1 = 4.67914826 \times 10^{-3}\ \mu m^2$, $B_2 = 1.35120631 \times 10^{-2}\ \mu m^2$ and $B_3 = 97.9340025\ \mu m^2$ [14].

Two big magnetic fluid (Fe_3O_4) infiltrate holes are situated around the centre of the fiber. The refractive index of infiltrate magnetic fluid is represented by n_i. As the refractive index of Fe_3O_4 is higher than the background material silica so the two infiltrate holes forms two separate cores and propagating light is confined in these two cores due to index guiding mechanism. Also refractive index of magnetic fluid changes with the varying external magnetic fields. Here we consider the fundamental propagating mode as it interacts directly with magnetic fluid infiltrated in two

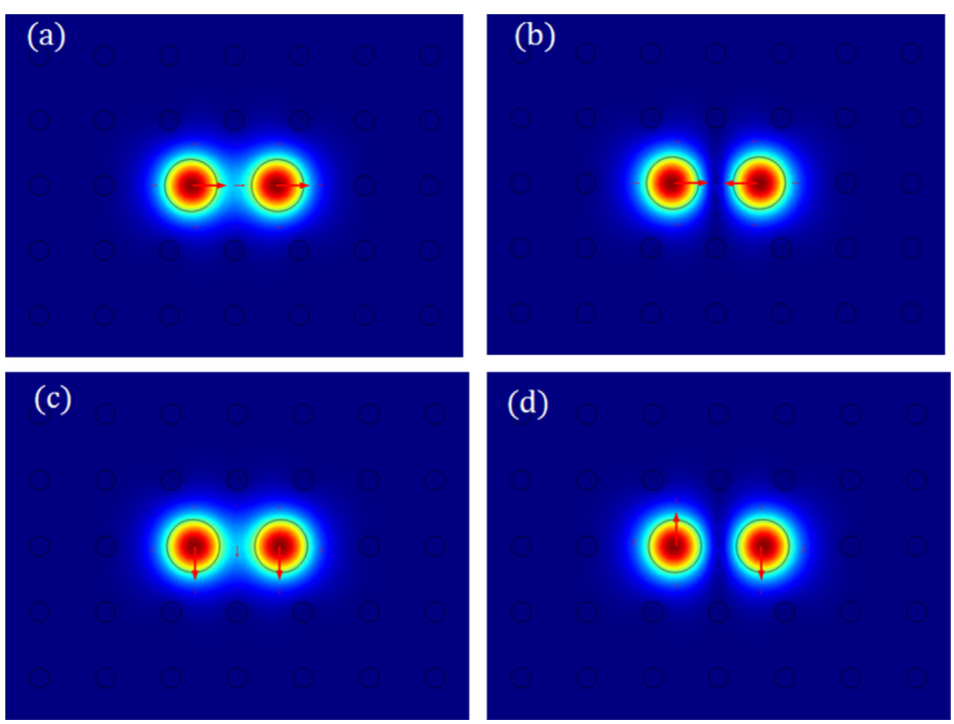

Fig. 2. Power flow distribution of the four supermodes of the designed DCPCF sensor: (a) x polarized even mode, (b) x polarized odd mode, (c) y polarized even mode, and (d) y polarized odd mode. Arrows represents corresponding electric field vectors for, $\wedge = 5.00\ \mu m$, $d_1 = 1.50\ \mu m$, $d_2 = 4.00\ \mu m$ and $n_i = 1.4635$.

Table 1
Refractive index variation of infiltrated magnetic fluid (Fe_3O_4) with applied magnetic field (H).

H (Oe)	89.9	120.3	150.0	180.4	210.9	240.6	271.0
n_i	1.4635	1.4645	1.4654	1.4662	1.4666	1.4668	1.4670