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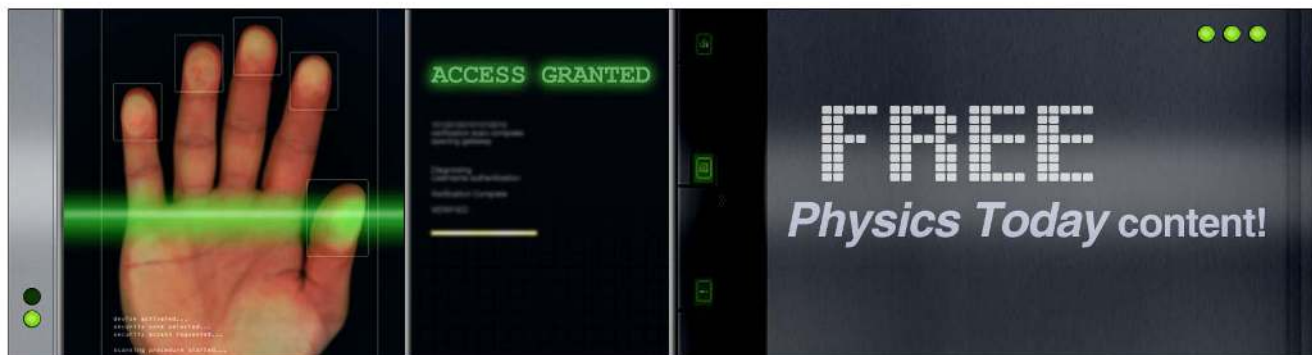
Magneto-optical fiber sensor based on bandgap effect of photonic crystal fiber infiltrated with magnetic fluid

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A magnetic field sensor based on combination of the magnetic fluid and the tunable photonic bandgap effect of photonic crystal fiber is proposed. The magnetic fluid with higher refractive index (>1.45) is prepared and filled into the air-holes of photonic crystal fiber to convert the index guiding fiber into photonic bandgap fiber. The proposed sensor takes full advantage of the ultrahigh sensitivity characteristic of photonic bandgap fiber and achieves a high sensitivity and resolution of 1.56 nm/Oe and 0.0064 Oe, respectively, which are 2-3 orders of magnitude better than other sensors based on magnetic fluid. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4772017]

Magnetic fluid (MF) is a promising function material which attracts a lot of research interests and finds a variety of applications in photonic devices due to its diverse magneto-optical effects such as refractive index tunability, birefringence effect, dichroism effect, Faraday effect, field dependent transmission, and so on.[1–5] Generally, in the optical devices, MF is employed either in the form of thin films in which light is transmitted and modulated, or in the form of reflective interface where the evanescent field of light is interacted at the surface layer of MF.[2,6–9] For example, several magnetic field sensors were demonstrated by using the MF films in optical fiber interferometers like Sagnac or Fabry-Perot interferometer.[10,11] Various magneto-optical modulators were carried out by using MF as the outer cladding of tapered or etched fibers.[2] Since the thicknesses of MF films were only as thin as several tens of microns and the performance of the optical devices was limited, a polarization-maintaining-fiber assisted configuration with the attempts to improve the corresponding extinction ratio was also implemented.[6,8] Recently, with the great development of the optical fiber technology, a family of optical fibers emerges, namely photonic crystal fiber (PCF), microstructured fiber, or holey fiber. The flexible air-hole structures of PCFs and the ultrahigh sensitivity to refractive index make them excellent candidate as a platform for liquid filled optical devices, especially for optical sensors of refractive-index measurement nature.[12] For instance, Thakur realized a magnetic field sensor by infiltrating MF into the air-holes of a PM-PCF with a sensitivity of 24.2 pm/Oe.[13] Candiani presented a magnetic field controlled phase-shifted fiber grating by selectively filling MF into the air-holes in the cladding of a hollow core PCF.[14] However, it is well known that the significant advantage of PCF for sensing application is the photonic bandgap shift effect, which can improve the sensitivity dramatically. There are some challenges for demonstrating photonic bandgap effect by infiltrating PCF with MF to realize magnetic field sensing. The main challenges are the

refractive-index value of MF does not fulfill the condition of photonic bandgap effect and the absorption loss of MF is too huge to transmit light in a length longer than 100 μm.

In this work, we proposed and demonstrated a magneto-optical fiber sensor based on the bandgap tunability of PCF by infiltrating MF with high refractive index. The sensitivity of the sensor was dramatically improved.

MF is a stable translucent superparamagnetic colloidal suspension of ferromagnetic nanoparticles in a suitable liquid carrier. The ultra-fine nanoparticles (for example, Fe_3O_4 or Fe_2O_3), whose nominal diameter is smaller than 10 nm, is fabricated by chemical coprecipitation method.[5] In order to disperse the solid-state nanoparticles in an appropriate solvent uniformly, surface modification with compatible surfactant is necessary to be applied on the nanoparticles, which can prevent the nanoparticles from magnetic clumping or agglomerating. Oleic acid is the most commonly used surfactant, while water-based MF is most commonly used in the magneto-optical applications. Under zero magnetic field, the nanoparticles are dispersed homogeneously in the solvent, which is a mono-dispersion state. When the MF is subjected to a magnetic field, the nanoparticles begin to agglomerate to form magnetic columns and a phase separation occurs between the solid nanoparticles and the liquid solvent.[3] Meanwhile, the magnetic columns tend to align with the direction of magnetic field.[15] This change of the dispersion state of the nanoparticles subsequently affects the effective dialectical constant or refractive index of the MF. The initial refractive index of MF under zero magnetic field is dependent on the concentration of MF, whose value increases from the intrinsic refractive index corresponding to the liquid solvent linearly and continuously with the particle concentration of MF.[1] Under the external magnetic field, the refractive index of the MF increases slightly as the magnetic field strength is increased, whose variation trend follows a Langevin function. The variation range of the refractive index of MF also depends on the concentration of MF. The higher the concentration of MF, the larger the variation range of refractive index.[16] The magnetic field induced refractive index change of MF can be used for magnetic field sensing

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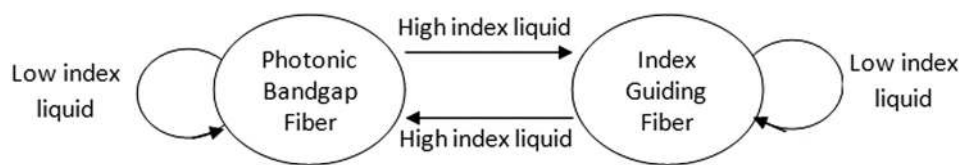
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FIG. 1. Conversion between the index guiding fiber and photonic bandgap fiber by filling liquid of high refractive index into the air-holes of the PCF.

measurement in a suitable refractometer structure. In this experiment, the PCF was chosen as a highly sensitive platform.

PCF is a kind of fiber based on the properties of photonic crystal, whose significant difference from traditional fiber is the introduction of periodic air-hole structures into the cross section of the fiber. If the refractive index of the core area is higher than the average refractive index of air-hole cladding (e.g., solid core PCF), its guiding mechanism is total internal reflection and it is classified as index guiding fiber. If the refractive index of the core area is lower than the average refractive index of air-hole cladding (e.g., hollow core PCF), its guiding mechanism is photonic bandgap effect and it is classified as photonic bandgap fiber. The index guiding fiber can be converted into photonic bandgap fiber by filling liquid into the air-hole structure. The only requirement is the refractive index of the liquid filled in should be higher than the refractive index of fiber material, pure silica ($n_s \approx 1.45$).[12,17] After filling the liquid with high refractive index into the air-holes of an index guiding PCF, the average refractive index of cladding becomes higher than the refractive index of the core area, so the liquid filled photonic bandgap fiber can be realized. The converting map between the two classes of PCFs is shown in Fig. 1. Photonic bandgap fiber exhibits a series of bands interrupted in wavelength, which depend on the refractive index of the liquid filled in. Therefore, sensing measurement can be carried out by monitoring the bands' shift.

The PCF used in the experiment was a solid-core index guiding fiber, LMA-10 (Fig. 2). Four hexagonally arranged air-hole layers surround the solid core in the cross section of the PCF. The core diameter, air-hole diameter, and pitch are 5.9 μm, 3.04 μm, and 6.26 μm, respectively.

MF with refractive index higher than 1.45 was prepared to covert the index guiding fiber into photonic bandgap fiber. Generally, the refractive index of water-based MF with a moderate concentration is lower than 1.45 since the refractive index of water is only 1.333.[1] Hence, we chose another solvent with a higher refractive index value, toluene, whose refractive index at room temperature is 1.497. In order to obtain a good sensitivity, the change of the refractive index of MF under external magnetic field should be as large as possible, so the MF with a high concentration is preferred. In the experiment, 10 mg dry ferromagnetic nanoparticles with fatty acid coating (EMG1200 from Ferrotech) were dispersed in 5.3 g toluene and then an ultra sound treatment was applied. After the treatment, we got a translucent uniform light brown MF with a mass concentration of 0.18%. Then, the MF was infiltrated into the air-holes of a 20-mm-length PCF solely by means of physical capillary effect. It took less than an hour to fill the whole length of the PCF.

We numerically simulated effective refractive-index maps on the basis of the given conditions to check whether a

bandgap can be supported in this MF filled PCF. The refractive index of MF was set to be 1.497. The plane-wave-expansion method was used to perform the simulation. As shown in Fig. 3(a), the light grey areas represent the supported bandgap modes. The transverse mode profiles of the MF filled PCF at different wavelengths were also computed. For example, Fig. 3(b) is the transverse profile at 900 nm and the light can be well confined in the core area, which means a bandgap exists at this wavelength; while Fig. 3(c) is the transverse mode profile at 1700 nm and the light radiates into the liquid-filled cladding, which means a reject band exists at this wavelength.

The experimental setup is shown in Fig. 2. The MF filled PCF was spliced in between two sections of single mode fiber by a common splicer for measurement convenience. The total splicing loss for the two splicing points was about 6 dB. A supercontinuum light source (500–1800 nm, NKT photonics A/S) and an optical spectrum analyzer (OSA, 600–1700 nm, AQ6370) were employed to monitor the transmission spectrum of the PCF. The magnetic field was generated with a Helmholtz coil (YL4020) and calibrated with a Gauss-meter. The MF filled PCF was placed in the uniform area of the Helmholtz coil and its length direction was aligned parallelly with the magnetic field direction. The experiment was conducted at room temperature of 23.7 °C.

The transmission spectra of the MF filled PCF under different magnetic field strengths are shown in Fig. 4. The blue curve indicated by "0 Oe" is the transmission spectrum of the magnetic field sensor under zero magnetic field. Four distinct pass bands appear on the spectrum from 600 nm to 1700 nm with assigned number of band 1 to band 4, which shows that the original index guiding fiber is converted to photonic bandgap fiber by filling the MF into the air-holes. Band 2 is the widest (about 200 nm) and most intact. Particularly, band 2 has a very sharp right edge with a high out-of-noise ratio of 35 dB. Therefore, band 2 is ideal for monitoring the bandgap shift of the spectrum. As the magnetic field strength is increased from 0 Oe to 225 Oe with an interval of 15 Oe, band 2 becomes wider and its right edge shifts to the longer wavelength side from 1041 nm to 1105 nm totally 64 nm.

The bandgap shift (edge shift) during the change of the magnetic field strength was recorded in order to evaluate the sensitivity of the sensor. The wavelength of the right edge of
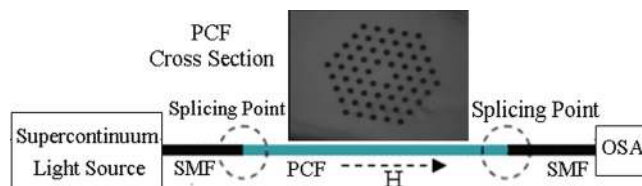

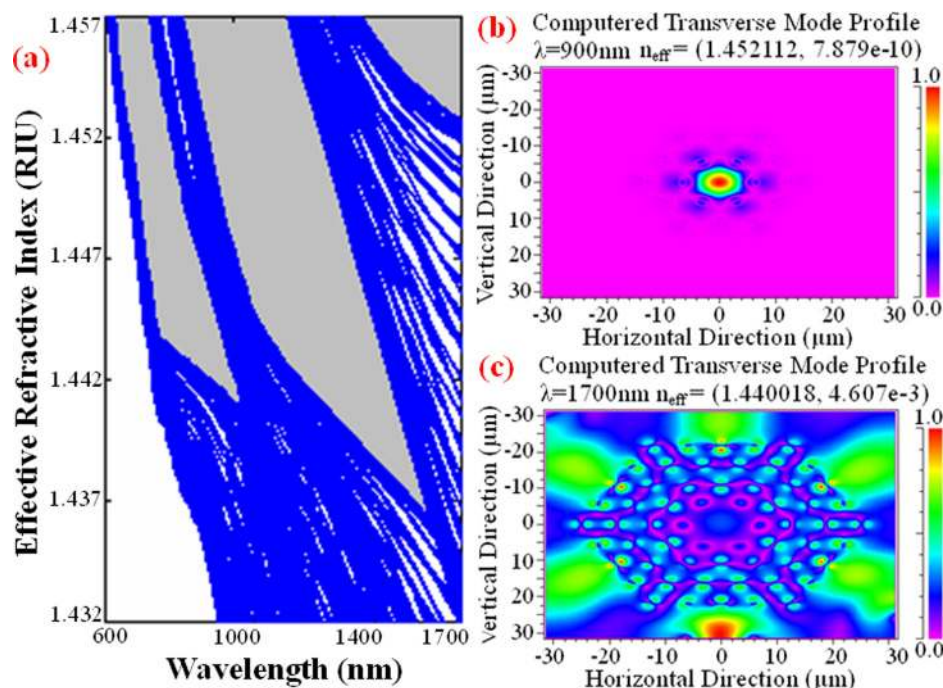FIG. 2. Experimental setup and the cross section of PCF.

FIG. 3. (a) Simulated effective refractive-index maps and computed transverse mode profile at (b) 900 nm and (c) 1700 nm.

the band 2 at −75 dBm, for example, is chosen to describe the bandgap shift which is plotted in Fig. 5. Fig. 5 shows that during the process of increasing the magnetic field strength, when it is lower than certain strength (saying H < 30 Oe), the edge wavelength shifts quickly and linearly; when it is higher than certain strength (saying H > 100 Oe), the edge wavelength shift tends to be saturated. The curve is fit by modified Langevin function with a high goodness-of-fit coefficient R^2 value.[7] Because MF is a superparamagnetic material, which means MF always returns to its original state when the applied magnetic field is removed, this proposed sensor also showed a good repeatability.[6,10] Linear fit method is also applied to the linear region of the curve and a sensitivity of 1.56 nm/Oe is achieved. In the literatures, Hu reported the magnetic field sensor based on Fabry-Perot interferometer with a sensitivity of 1.5 pm/Oe;[11] Liu proposed a filter based on long period grating with tunable sensitivity of 4.4 pm/Oe; the magnetic field sensor based on Sagnac interferometer and modal interference was also carried out in our previous work with sensitivities of 16.7 pm/Oe (Ref. 9) and 2.367 pm/Oe, respectively; Thakur filled the polarization maintaining PCF with MF and achieved a sensitivity of 24.2 pm/Oe; however, our experimental result is 1.56 nm/Oe,

which is 2–3 orders of magnitude better than these reported results. Considering the resolution limit 10 pm of the OSA, the resolution of this proposed sensor is estimated to be 0.0064 Oe.

It is worth noticing that though the MF with higher refractive index can be achieved by increasing the concentration of the water-based MF, it is not suitable for filling into the air-holes of PCF to perform this sensing measurement, because the nanoparticles contained within the high concentration liquid tend to agglomerate and adhere to the inner wall of air-holes irreversibly, which will fail the measurement. Therefore, MF with a higher refractive-index solvent is highly recommended in this sensing scheme.

In conclusion, a magnetic field sensor based on the tunable bandgap effect of the MF filled PCF is theoretically analyzed and experimentally demonstrated. The solid core index guiding fiber is converted to photonic bandgap fiber by filling the air-holes of the PCF with MF, whose refractive index is controllable with external magnetic field. The key to this sensor is the preparation of the toluene-based MF with a higher refractive index (higher than 1.45). The achieved sensitivity and resolution of the sensor are 1.56 nm/Oe and 0.0064 Oe, respectively, which are 2–3 orders of magnitude
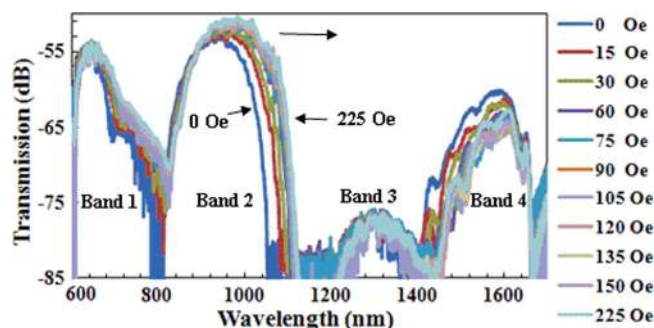

FIG. 4. Transmission spectra of the magnetic field sensor under different magnetic field strengths.
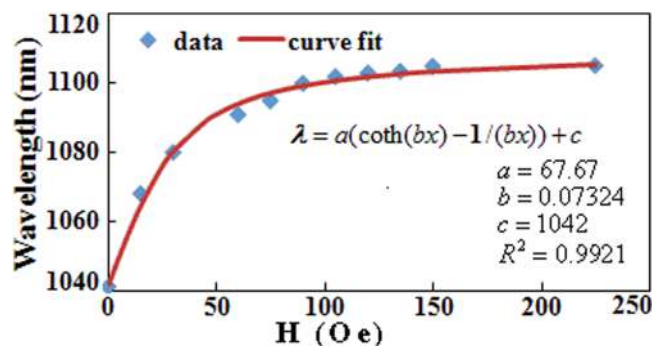

FIG. 5. Variation trend of the edge wavelength vs the magnetic field strength.

better than the reported MF-based sensor. The sensor also has the merits of simple fabrication, low cost, and miniature structure.

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