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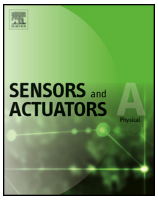

Laser-sculpted hybrid photonic magnetometer with nanoscale magnetostrictive interaction

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ABSTRACT

We present a new photonic magnetic sensor that can yield information on the spatial angle of rotation of the sensor within a given static magnetic field that based upon an optical fiber platform that has a wavelength-encoded output and a demonstrated sensitivity of 543 pm/mT. This optical fiber magnetic field sensor combines a conventional, UV-laser inscribed long period grating (LPG) with a magnetostrictive material Terfenol-D that coats and fills 50-μm micro-slots running adjacent and parallel to the fiber central axis. The micro-slots are produced using a femtosecond laser and selective chemical etching. A detection limit for a static magnetic field strength of ±50 μT is realized in low strength DC magnetic field (below 0.4 mT), this performance approaches the Earth's magnetic field strength and thus, once optimized, has potential for navigation applications. Our method addresses the major drawback of conventional sensors, namely their inadequate sensitivity to low strength, static magnetic fields and their inability to provide information about the orientation and magnitude.

1. Introduction

There is significant interest in detecting and monitoring electromagnetic fields (EMF) generated in a number of industries, for applications related to process control, electric field monitoring in medicine, ballistic control, electromagnetic compatibility measurements and the potential health risks associated with environmental exposure to overhead power cables [1,2]. Other potential applications have been explored such as current sensors, load cells, accelerometers, proximity sensors, non-contact torque sensors and magnetometers [3–6]. Specifically, magnetometers are widely used for navigation and in geophysical research involving measuring the Earth's magnetic field (25–65 μT) [7]. There is interest in using optical fiber sensors that stems from their many advantages; they have high reliability, with low maintenance requirements, immunity to high voltage and electromagnetic interference, light weight, compactness and the capability to function in many hostile environments where conventional sensors would possibly fail. Orthodox EMF measurement systems are based on an active metallic probe that can perturb the EMF being sensed. Moreover, this sensing approach is susceptible and vulnerable to electromagnetic noise [8]. There are other types of magnetic field sensors that are based upon on different magnetic effects. These types of sensors include, one, magnetoresistance sensors [9] which are generally sensitive to a magnetic field applied in a single direction but they can have issues with angular cross-field errors and possible saturation response with small field strengths. Two, magnetoimpedance which are used to measure alternating magnetic field and not static magnetic fields, furthermore some of the materials used produce stripe domains [10] that can affect the performance of the sensor and complex designs are been used with varying success [11]. Three, anisotropic magnetoresistance but typically don't have good sensitivity to measure low strength DC magnetic fields [12]. Again, the aforementioned three effects are measured electrically which have the same vulnerable as the conventional EMF detection systems. In contrast, the sensing of EMF with fiber optic sensors demonstrates great benefits compared with electronic devices; these beneficial attributes include excellent galvanic insulation, high sensitivity and very large bandwidth.

There are a myriad of fiber optic sensing platforms for detecting magnetic fields that utilize the magnetostrictive effect in specific materials. These ferromagnetic materials produce a strain in the

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direction of the magnetic field, thus generating a longitudinal strain within the optical fiber itself [3,13–15]. All of these fiber optic sensors have several operating deficiencies, principally, their poor performance leads to an inability to detect low static magnetic field strengths. Researchers have used an array of magnetostrictive fiber optic to yield directional information and magnitude of the applied magnetic field [16,17] but operated in high strength magnetic fields and poor sensitivity to low strength fields. Furthermore, from the literature there is no reported sensitivity dependence on orientation within a magnetic field for single magnetostrictive fiber optic sensor. There are other types of optic fiber sensor that yield magnetic field orientation, such as, those based upon the interaction of guides modes or surface plasmons with magnetic fluids [18,19], again these sensors have a poor performance in detecting low static magnetic fields.

We present here a new optical fiber magnetic field sensor, comprising a conventional UV-laser inscribed long period grating (LPG) adjacent to 50-μm long micro-slots that are located parallel to the fiber central axis. The micro-slots were delineated using a femtosecond laser and revealed by a hydrofluoric acid etching process [20]. The fiber was coated, and the micro-slots filled, with Terfenol-D, a magnetostrictive material, by using sputtering technology. This new optical fiber magnetic field sensor has a very high maximum spectral sensitivity to B-field ($\Delta\lambda/\Delta B$ of −543 pm/mT), an optimum resolution of ±50 μT for magnetic field strengths below 0.4 mT and a resolution of ±100 μT above 1 mT.

The LPG attenuation band response to B-fields exhibits both red and blue spectral shifts; these change in wavelength is dependent upon the spatial orientation of the sensor to the magnetic field. The wavelength shifts produced by the fiber devices are a combination of geometrical shape birefringence, created by the micro-slots/Terfenol-D monoliths, and stress induced birefringence produced by the Terfenol-D in response to a DC magnetic field (expansion or contraction), along with changes to the polarization state of the illuminating light produced by rotation of the fiber.

The investigation is to create a single optical fiber magnetic field sensor to that as a marked improvement in performance over the existing fiber optic sensors with regards to sensitivity, limit of detection and to have the intrinsic ability to differentiate various directions of the DC magnetic fields. Furthermore, to achieve an increase in performance such that the earth's magnetic field can be detect with such a fiber optic magnetometer offers various applications already mentioned above. Whilst our device is not a true vectorial fiber optic magnetic field sensor, nevertheless it offers information on the orientation and magnitude of the sensor within a DC magnetic field. We note that the Faraday effect can be exploited for such purposes [21], but the Verdet constant is very low in glass, thus limiting the range of potential applications to those where large field strengths are present, for example as a magnetic field sensor for use in high power, electrical machinery. Furthermore, the resolution of this type of fiber optic magnetometer in low strength DC magnetic field is ±50 μT which is approaching the values of the earth's magnetic field (25–65 μT).

2. Magnetic sensor modelling

An LPG structure was chosen over a fiber Bragg grating [22], based on earlier experimental investigations that showed the latter provided lower sensitivity [3]. The LPG's phase matching condition has many dependent parameters, in particular, the cladding effective index, and the Terfenol-D monoliths in our structures, can regionally change this value in the presence of a magnetic field. Moreover, the transmission spectra of LPGs written into asymmetric fibers (in this case caused by the femtosecond laser microslots) can yield information on the orientation of any bend experienced by the fiber [23].

The period of the LPG was chosen so that the attenuation bands coincided with the bandwidth of the available light sources. This involved calculating the propagation constants for the core and cladding modes [24] (the optical fiber is commercial grade SMF-28 from Dow Corning Inc.) over a range of wavelengths and producing phase matching curves, leading to a suitable period of 430 μm. For this period, there are several attenuation bands present from 1300 nm to 1700 nm (Fig. 1 a). The second step was to determine the spatial position of the Terfenol-D monoliths, with reference to the core of the optical fiber, which yields the greatest perturbation on an individual cladding mode, and thus higher, geometrical shape birefringence. This was estimated by using a Finite Element Method software package (Comsol) to inspect the radial E-field distributions of the cladding modes and looking at the largest overlap between the monolith and the E-field at a radial distance from the core sufficient to yield asymmetric spectral behavior. In the presence of magnetic field the monoliths would produce detectable, asymmetric strains dependent on the direction of any local magnetic field. This radial distance was estimated to be approximately 28 μm (Fig. 1b). The monolith length of 50 μm and width of 10 μm was chosen from previous work [25]. Increasing the size of the micro-slots and their number causes an increase in mechanical fragility [25], so this size represents something of a compromise. The final step was to estimate the strain-inducing effect of the Terfenol-D in a magnetic field and thereby determine the change in the effective refractive index of the cladding glass by using the strain-optic coefficient of SMF-28 (0.24) [24], as a first approximation. Furthermore, if the fiber with the sensor is rotated, the authors realize this rotation will generate additional torsional strain (via the strain-optic coefficients [26]; $p_{4,4}$) inducing elliptical birefringence and change the polarization. This rotational action in an asymmetric fiber (possessing elliptical birefringence), when rotated clockwise or anticlockwise, results in increasing or decreasing birefringence [27]. Hence the Terfenol-D monolith, with the correct orientations to the magnetic field, can produce stress to either add or reduce the local birefringence, resulting in red or blue wavelength shifts of the LPGs attenuation bands. The calculation of the induced strain was undertaken in several steps. Using information provided by the manufacturer of the Terfenol-D [3], and assuming an ideal mechanical coupling between the monoliths and the glass, the magnetic field induced radial variation in the effective index was included in a FEM model of the machined fiber incorporating the Terfenol-D. An example of radial variation in strain across the optical fiber is shown in Fig. 1c, and an example of the perturbed E-field of a cladding mode in the perpendicular plane of travel is shown in Fig. 1d.

Using the FEM model for different strength magnetic fields and including the spatial orientation of the B-field lines, the model allowed us to calculate variations in the propagation constants associated with magnetic field strength and orientation. This approximation assumes that the propagation constants already incorporate the shape birefringence, and the Terfenol-D stress-induced birefringence, caused by the radial generated strain by the Terfenol-D monoliths in the presents of static magnetic field, can be calculated using the approach given in REF 28, which includes the assumption that stress contribution wavelength dependence P_λ is attributed to chromatic dispersion of the stress optical coefficient given in REF 28, thus the stress birefringence Δn_{stress} and polarization dispersion P_λ:

$$\Delta n_{stress} = PS_{max} \; and \; P_\lambda = \frac{S_{max}}{c}\left(P - \lambda\frac{dP}{d\lambda}\right)$$

Where P is the stress optical coefficient, S_{max} is the maximum difference in the radial stress/strain produced by the Terfenol-D