Invited Paper

Fiber optic sensing of magnetic fields utilizing femtosecond laser sculpted microslots and long period gratings coated with Terfenol-D

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ABSTRACT

Fiber optic sensors are fabricated for detecting static magnetic fields. The sensors consist of a UV inscribed long period grating with two 50 micron long microslots. The microslots are fabricated using the femtosecond laser based inscribe and etch technique. The microslots and the fiber surface are coated with a magnetostrictive material Terfenol-D. A spectral sensitivity of 1.15 pm/mT was measured in transmission with a working resolution of ±0.2 mT for a static magnetic field strength below 10 mT. These devices also present a different response when the spatial orientation of the fiber was adjusted relative to the magnetic field lines.

Keywords: magnetic sensing, long period gratings, femtosecond laser, etching, optical fibers

1. INTRODUCTION

In recent years there has been an increased interest in electromagnetic fields (EMF) and thus the sensors for measuring the fields, with applications in various areas of science and technology such as process control, electric field monitoring in medical apparatuses and the potential health risks caused by environmental exposure to artificial sources such as overhead power cables/pylons [1, 2]. The conventional EMF measurement systems currently use active metallic probes which can disturb the measuring EMF and make the sensor very sensitive to electromagnetic noise. Fiber optic EMF sensors have shown great advantages with respect to the electronic devices such as a very good galvanic insulation, high sensitivity and very wide bandwidth. Many magnetic field optical sensors exploit the magnetostrictive effect, creating a strain in a ferromagnetic material in the direction of the magnetic field and producing a longitudinal strain in an optical fiber adhered to the material [3, 4]. A magnetic field sensor using magnetic fluid and an optical microfiber mode interferometer has also been demonstrated [5, 6]. All of these fiber optic sensors are non-vectorial and have relatively low sensitivity to static magnetic field strengths.

In this paper we demonstrate a fiber optic magnetic field sensor based on a long period grating (LPG) and two microslots enabling a relatively high spectral sensitivity (1.15 pm/mT) to a low magnetic field strength (of less than 10mT) with a resolution of 60 µT and the potential for vectorial sensing. These sensors are based on a UV inscribed LPG with two 50 µm long microslots parallel to the fiber core longitudinal axis, with sputtering technology used to adhere a magnetostrictive material - Terfenol-D to the optical fiber and the microslots.

2. DEVICE FABRICATION AND CHRACTERISATION

2.1 Device design & fabrication

The first step in fabricating the magnetic sensor begins with the inscription of the LPG in hydrogenated standard single mode fiber (Corning SMF-28e). The LPG was inscribed with a 244 nm UV laser (Coherent Sabre Fred) with an average laser power of 100 mW using the point-by-point inscription method [7]. The LPG was 30 mm in length with a grating period of 430 µm. The in-fiber microslots were fabricated using the femtosecond laser based inscribe and etch technique [8, 9]. The inscription was performed using an Amplitude Systèmes s-Pulse HP femtosecond laser that produces sub 500

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fs laser pulses at a center wavelength of 1026 nm. Laser inscription was carried out under a 100x objective (Mititoyo MPlan Apo NIR Series) with a numerical aperture of 0.5. The approximate FWHM of the laser spot size incident on the samples was 1.5 µm. Details on the mounting configuration and method for inscribing each microslot can be found in the following reference [9]. Two 50 µm microslots separated by 70 µm, with an offset of 28 µm from the core edge were inscribed in the mid position of the LPG with a pulse energy of 350 nJ, as illustrated in Figure 1a. This distance was chosen to provide the maximum effect on the cladding modes associated with the LPG with a period of 430 mm and an attenuation band around 1500nm, which corresponds to the $HE_{1,4}$ and possibly $HE_{1,5}$ cladding modes for a conventional SMF [10]. After inscription the sensor was etched in a 5 % hydrofluoric acid solution assisted by an ultrasonic bath for approximately 25 minutes. The device after etching is shown in Figure 1b and c. The final step to functionalize the sensor was to back fill the microslots and to apply a uniform layer of Terfenol-D on the fiber using a sputter machine and mask to achieve a coating thickness of 1µm [3].

(a) (b) (c)

Figure 1. (a) Schematic of the magnetic optical fiber design – femtosecond laser inscribed and etched microslots positioned at the midpoint of the UV inscribed LPG. Image of the in-fiber microslots after femtosecond laser inscription and HF treatment - (b) top view focused at the center of the microslots and (c) side view showing the microslots passing through the whole fiber.

2.2 Device characterization

The magnetic sensor was subjected to a range of magnetic field strengths and interrogated in transmission as illustrated in Figure 2a. A broadband light source containing a series of ELEDs (Agilent 83437A, 1260nm to 1690nm) passed through a broadband motorized linear polarizer (PAT8000B), a manual polarization controller and polarimeter prior to illuminating the magnetic sensor. The transmission spectrum was observed using an OSA (Agilent 86142B). With reference to Figure 3a, magnetic fields from a ring magnet and a horseshoe magnet were used to test the fiber sensor response. The strength of each magnet was measured using a Gauss meter. The thermal sensitivity of the device was tested using a Peltier heater. The temperature sensitivity of the magnetic sensor was characterized between 20 °C – 60 °C and calculated using the change in centroid wavelength. A linear thermal sensitivity of 12.6 pm/°C and 16.2 pm/°C was observed for the modes in the 1435 nm and 1550 nm regions respectively.

(a) (b) (c)

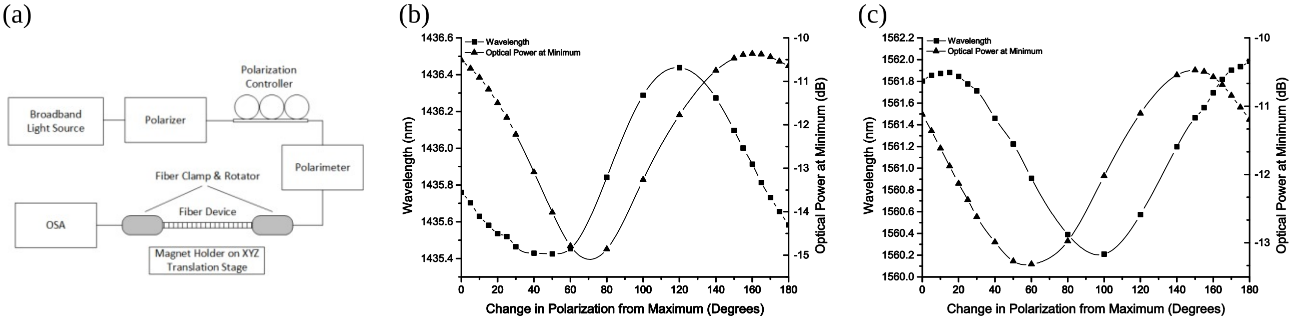

Figure 2. (a) Device characterization measurement configuration. Variation in the centroid wavelength and the effective optical strength of the transmission spectra, as a function of polarization. Two microslot device polarization responses in the (b) 1430 nm and (c) 1550 nm region.

The polarization dependence of the two strongest modes in the 1430 nm and 1550 nm regions were studied. Given that the microslots occupy one plane through the optical fiber, there is a 90º separation between one maximum to the following minimum.

3. RESULTS AND DISCUSSION

Two magnets were used in the following tests - a 6.4 kg pull ring magnet and a 4.5 kg pull horseshoe magnet. The ring magnet was used to examine the sensitivity of the magnetic fiber sensor in small magnetic fields (< 10mT). The horseshoe magnet was used to evaluate the sensitivity of the magnetic sensor in much larger magnetic fields (> 10mT) and to illustrate the potential of using the fiber device as a vectorial sensor. With the fiber sensor positioned in the hole of the ring magnet, the magnet was translated over and away from the microslots and thus subjected the fiber sensor to small magnetic fields. Figure 3a shows the magnet and optical fiber configuration. The spectral response of the fiber sensor at each magnetic field strength was recorded and a centroid peak-fitting algorithm was used to track the wavelength resonance.

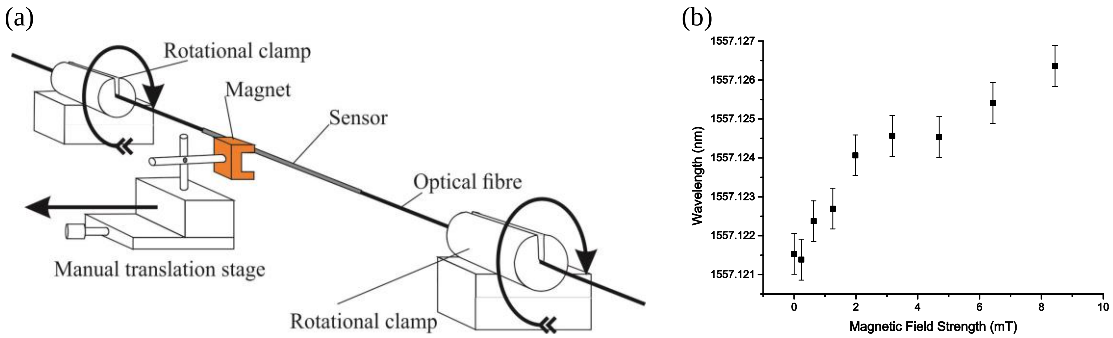

Figure 3. (a) Magnet and fiber sensor arrangement – diagram shows a magnet mounted to a 3D translation stage and the fiber sensor held in rotational clamps. (b) Variation in the centroid wavelength (1550 nm region) in response to small magnetic field strengths generated by a 6.4 kg pull ring magnet translated across the fiber sensor.

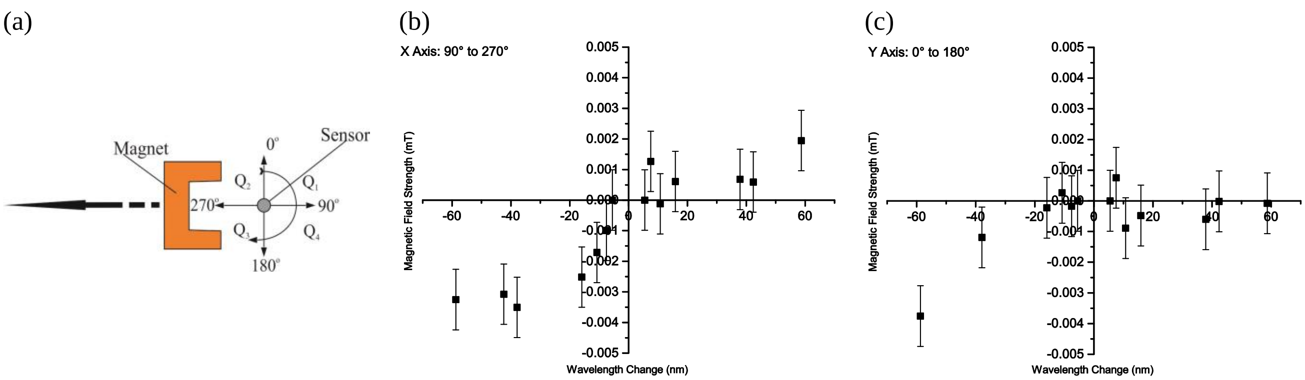

Figure 4. (a) Horseshoe magnet relative to the magnetic fiber sensor X and Y axis. Wavelength variation in response to strong magnetic field strengths in the (b) X axis 90º to 270º and (c) Y axis 0º to 180º.

The sensor's resolution was determined by using the procedure in [11] providing a magnetic field strength resolution of ~60 μT over the range of a few mT and the results are shown in Figure 3b. A spectral sensitivity of 1.15 pm/mT was measured in transmission with a working resolution of ±0.2 mT for a static magnetic field strength below 10 mT. These devices have a spectral temperature sensitivity of 12.6 pm/°C and 16.2 pm/°C along with an average polarization dependence of 7 pm/degree. Cross-talk between the magnetic field strength and temperature has been calculated using the experimental data obtained and other material constants from references [12] yielding a small and insignificant value $\sim 7\times10^{-3}$ pm°C^{-1}mT^{-1}.

Using the 4.5 kg pull horseshoe magnet, the fiber sensor was subjected to large magnetic fields strengths. This was achieved in a similar manner to the ring magnet configuration, however, in this instance the horseshoe magnet was held at the side of the fiber. The horseshoe magnet was then translated away from the fiber to vary the strength of the magnetic field imposed on the optical sensor. With reference to Figure 4a, this test was repeated at four positions on the fiber by using the fiber rotation clamps. The wavelength variation in response to the different magnetic field strengths relative to the orientation of the fiber sensor is shown in Figure 4b and c. The overall sensitivity compared to the previous experiment is less. This is expected, due to the fact that the magnetic field direction (along the axis of the fiber) is chosen to obtain the maximum response of the Terfenol-D monoliths within the optical fiber. Here the spectral sensitivity is 0.05 pm/mT, which is significantly lower than for the experimental data shown in Figure 3b. This can be improved by increasing the number of monoliths in the sensor. What is significant is that the wavelengths are opposite and with approximately the same magnitude in the spectral sensitivity along the 0^o and 180^o orientation, along the positive and negative Y axis. Similarly the spectral response of the sensor along the 90^o and 270^o orientation, along the positive and negative X axis, again shows a distinctive response to those two orientations. Ideally a similar behavior to that of Figure 4b would have been observed. It is suspected that the maximum response in the positive X direction is at a different angle, and that the different Terfenol-D monoliths are asymmetric in strength response due to the amount of material in each microslot that constitutes the monolith.

4. CONCLUSION

Fiber optic sensors were fabricated for the application of detecting and measuring static magnetic fields. The sensor consisted of a UV inscribed LPG with two 50 micron long microslots parallel to the fiber core longitudinal axis. The microslots were fabricated using the femtosecond laser based inscribe and etch technique, which allows full control of the size, shape and position of the microslots. The microslots and the fiber surface were coated in Terfenol-D. A spectral sensitivity of 1.15 pm/mT was measured in transmission with a working resolution of ±0.2 mT for a static magnetic field strength below 10 mT. In addition, these devices provide different responses when the spatial orientation of the fiber is changed relative to the magnetic field lines, thus showing potential of being true B-field sensors measuring magnitude and direction.

REFERENCES

[1] Stavroulakis, P., [Biological effects of electromagnetic fields] Springer, (2003).

[2] Sienkiewicz, Z., “Biological effects of electromagnetic fields,” Engineering Science & Education Journal, 7(3), 127-134 (1998).

[3] Smith, G. N., Allsop, T., Kalli, K., Koutsides, C., Neal, R., Sugden, K., Culverhouse, P., and Bennion, I., “Characterisation and performance of a Terfenol-D coated femtosecond laser inscribed optical fibre Bragg sensor with a laser ablated microslot for the detection of static magnetic fields,” Optics Express, 19(1), 363-370 (2011).

[4] Silva, R. M., Chesini, G., Gouveia, C. J., Lobo Ribeiro, A. B., Frazão, O., Cordeiro, C. M. B., and Jorge, P. A. S., "Magnetic field sensor with Terfenol-D thin-film coated FBG." 8421, 84213C-84213C-4.

[5] Zheng, Y., Dong, X., Chan, C. C., Shum, P. P., and Su, H., “Optical fiber magnetic field sensor based on magnetic fluid and microfiber mode interferometer,” Optics Communications, 336(0), 5-8 (2015).

[6] Deng, M., Liu, D., and Li, D., “Magnetic field sensor based on asymmetric optical fiber taper and magnetic fluid,” Sensors and Actuators A: Physical, 211(0), 55-59 (2014).

[7] Hill, K. O., Malo, B., Vineberg, K. A., Bilodeau, F., Johnson, D. C., and Skinner, I., “Efficient mode conversion in telecommunication fibre using externally written gratings,” Electronics Letters, 26(16), 1270-1272 (1990).

[8] Lai, Y., Zhou, K., Zhang, L., and Bennion, I., “Microchannels in conventional single-mode fibers,” Opt. Lett., 31(17), 2559-2561 (2006).

[9] Lee, G. C. B., Mou, C., Zhou, K., and Sugden, K., "Optimization and characterization of femtosecond laser inscribed in-fiber microchannels for liquid sensing." Proc. SPIE 9157, 915743-915743-4 (2014).

[10] Allsop, T., Webb, D. J., and Bennion, I., “A comparison of the sensing characteristics of long period gratings written in three different types of fiber,” Optical Fiber Technology, 9(4), 210-223 (2003).

[11] Hu, J., Sun, X., Agarwal, A., and Kimerling, L. C., “Design guidelines for optical resonator biochemical sensors,” Journal of the Optical Society of America B, 26(5), 1032-1041 (2009).

[12] Ghosh, G., [Handbook of Thermo-Optic Coefficients of Optical Materials with Applications] Academic Press, (1998).