A Magnetostrictive Sensor Interrogated by Fiber Gratings for DC-Current and Temperature Discrimination

J. Mora, A. Díez, J. L. Cruz, and M. V. Andrés

***Abstract*—A magnetostrictive sensor head with temperature compensation has been developed for measurement of static magnetic fields. The device consists on two different alloys with similar thermal expansion coefficient one of which has a giant magnetostriction, the expansion of both materials produced by heat and magnetism is detected by two fiber gratings. One of the gratings measures the temperature of the sensor and the difference between the wavelengths reflected by the gratings is a measurement of the magnetically induced strain.**

***Index Terms*—Fiber gratings, magnetostriction.**

I. INTRODUCTION

OPTICAL fiber gratings are being used as sensors of a number of physical magnitudes as temperature, strain and pressure; other magnitudes like electric or magnetic fields can be detected by fiber gratings using appropriate transducers. In principle a fiber grating can detect magnetic fields by Faraday effect. This mechanism is ideal because it does not need an external transducer but his sensitivity is too low for practical applications [1]. Different transducers have been developed to improve the grating sensitivity. For ac-current measurement these transducers consist of a conventional current transformer whose secondary output is used to heat a grating by a metallic coating [2] or to stretch the grating by a piezoelectric ceramic [3]. For dc-current measurement magnetostrictive materials have been successfully used as current transducers. In a first approach a metallic glass strip was used as phase modulator in a fiber interferometer [4] and in a second approach a metallic glass was used to dither the Bragg wavelength of a fiber grating at the input of an interferometric detection system [5]. Finally, materials with giant magnetostriction [6], [7] and magnetic forces between magnets [8] have been recently used to tune fiber gratings. These devices are potentially suitable to operate as current sensors.

The above detection procedures are sensitive to the temperature of the head sensor, in particular those based on fiber gratings. Magnetostrictive alloys with saturation strains greater than 1000 ppm can shift the Bragg wavelength of a fiber grating about 1 nm with a magnetizing field of the order of 100 mT [6], [7]. This is comparable to wavelength changes generated by temperature fluctuations, depending on the bonding material a fiber grating shifts between 1 and 3 nm when the room temperature varies in 100 °C. Furthermore the magnetostriction of these materials has an intrinsic dependence with temperature of the order of 5 ppm/°C [9]. Hence, these sensors must operate at stabilized temperature or alternately the must compensate the effect of temperature variations.

In this paper we present a magnetostrictive sensor for dc magnetic fields interrogated by two fiber gratings that measures simultaneously electric current and temperature. The sensor is essentially formed by two different alloys in thermal equilibrium being one of them a magnetostrictive compound and having

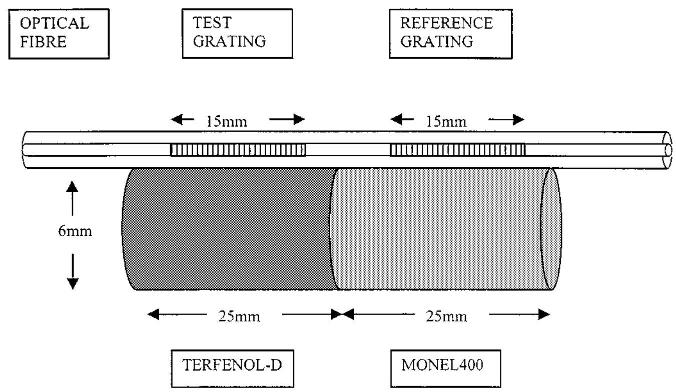

Fig. 1. Schematic diagram of the sensor head.

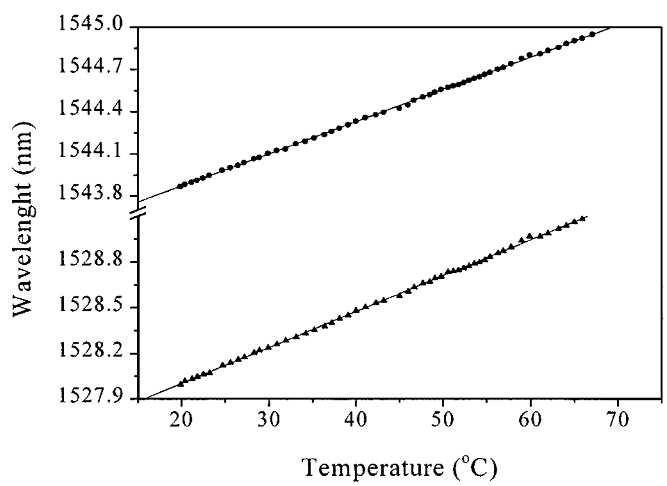

Fig. 2. Wavelength variation of the two gratings produced by temperature in absence of magnetic field. ●: test grating and ▼: reference grating.

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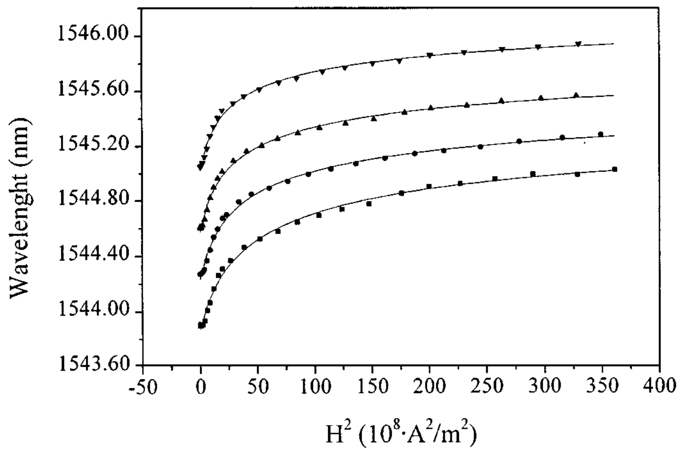

Fig. 3. Wavelength reflected by the grating mounted on the magnetostrictive rod as function of the applied field at different temperatures. ■: 21.6 °C; •: 37.4 °C; ▲: 53.3 °C; and ▼: 73.7 °C.

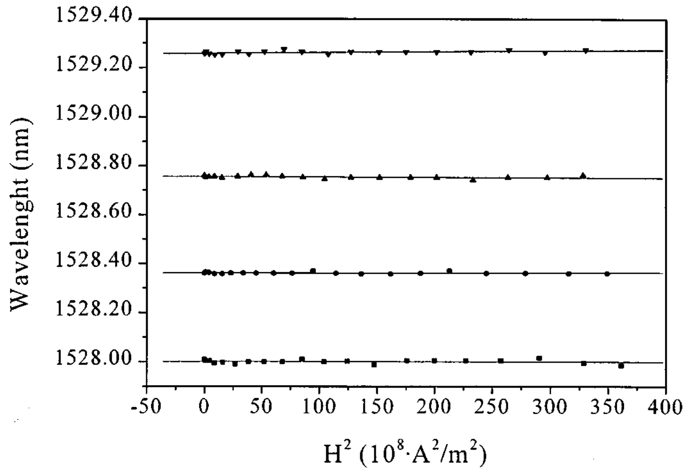

Fig. 4. Wavelength reflected by the reference grating as function of the magnetic field at different temperatures. ■: 21.6 °C; •: 37.4 °C; ▲: 53.3 °C; and ▼: 73.7 °C.

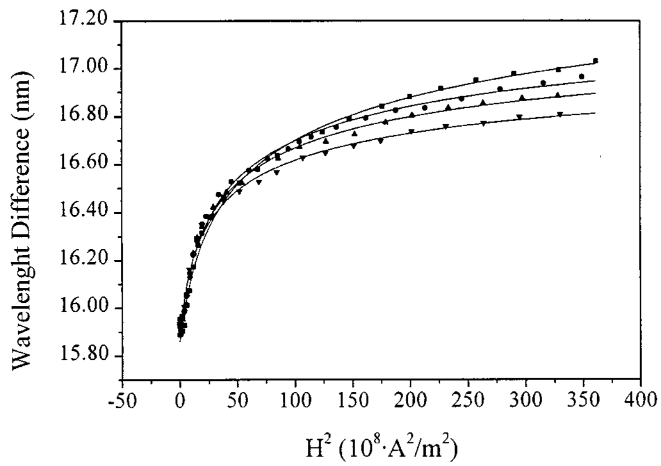

Fig. 5. Difference between the Bragg wavelengths reflected by the gratings as a function of the applied field at different temperatures. ■: 21.6 °C; •: 37.4 °C; ▲: 53.3 °C; and ▼: 73.7 °C.

both the same thermal expansion coefficient. When the magnetostrictive material is subjected to a magnetic field it suffers an elastic lengthening and the Bragg wavelength of his grating shifts to longer wavelengths. Because both gratings have the same thermal expansion, when temperature increases it follows that the difference between the Bragg wavelength of the gratings is a measurement of the magnetostriction and the wavelength of the grating bonded to the non magnetic alloy is a measurement of the temperature.

II. Experiment

The sensor head consists on two rods of two different alloys spliced together as it is shown in Fig. 1. The fist rod is made of Terfenol-D, a magnetostrictive material that has a giant magnetostriction of the order of 1000 ppm for a magnetizing field of 100 mT when it operates at room temperature free of mechanical stress. The saturation field depends on the mechanical load and increases from 100 mT to 500 mT for loadings in the range 0–100 MPa. Terfenol-D operates efficiently at low frequencies in the region 0–5 kHz, the material can be laminated for operation at higher frequencies but some special specimens have a binder into the metal matrix composite that gives electrical insulation between the grains of terfenol and reduces the eddy current losses up to 25 kHz and even higher frequencies. The second rod is made of Monel-400 an alloy of composition Ni65/Cu33/Fe2. Both materials have a similar thermal expansion coefficient with a nominal value of $\alpha_B = 14.0 \times 10^{-6}\,^\circ\mathrm{C}^{-1}$. The rods have a length of 25 mm and a diameter of 6 mm.

A fiber grating was held to each rod to detect his expansion when heat or a magnetic field is applied. The fiber was epoxy-bonded to the alloys and introduced in a furnace at 70 °C for three hours to cure the glue and to anneal the gratings before operation. The gratings were written in a boron codoped germanosilicate fiber by irradiating the fiber with a doubled argon laser through a phase mask. The gratings are 15 mm in length they have a peak reflectivity of 75%, a bandwidth of 0.12 nm and the Bragg wavelength of each grating was 1527.97 nm and 1543.8 nm at 20.0 °C after thermal annealing.

The thermal behavior of both materials was measured by heating the sensor in a stabilized oven from 20 °C to 67 °C. The wavelength variations are shown in Fig. 2. Both gratings exhibit a linear response, the first grating mounted on Terfenol has a sensitivity of 0.0239 ± 0.001 nm/°C while the sensitivity of the second grating mounted on Monel-400 is 0.0240 ± 0.001 nm/°C. Hence, if the sensor temperature increases in 100 °C, the difference between the wavelengths reflected by the gratings will change in about 0.01 nm.

We can calculate the expansion coefficient of the two sections of the sensor. The wavelength shift $\Delta\lambda$ induced by temperature in a grating mounted on a cantilever of thermal expansion coefficient α_B is

$$\Delta\lambda/\Delta T = \lambda[(\alpha_B - \alpha_F)(1 - p_e) + \alpha_F + \zeta] \qquad (1)$$

where

ΔT temperature change;

α_F thermal expansion coefficient of the fiber;

ζ thermooptic coefficient;

p_e stress-optic coefficient.

We have previously measured in two separate experiments the values of p_e and $\alpha_F + \zeta$ in our fiber, we have obtained $p_e = 0.304$ and $\alpha_F + \zeta = 5.75 \times 10^{-6}$ °C^{-1}. The thermal expansion coefficient of the fiber (α_F) is assumed to be equal to the expansion coefficient reported in the literature for fused quartz $\alpha_F = 0.55 \times 10^{-6}$ °C^{-1}. Substituting these constants in equation (1) we have obtained $\alpha_B = (14.4 \pm 0.5) \times 10^{-6}$ °C^{-1} for Terfenol-D and $\alpha_B = (14.8 \pm 0.5) \times 10^{-6}$ °C^{-1} for Monel-400.

For small magnetizing fields the magnetostrictive response of an alloy follows the coherent model and has a quadratic dependence on the applied field H [4], hence the fractional wavelength shift induced in the grating by simultaneous action of magnetostriction and heat is

$$\Delta\lambda/\lambda = (1-p_e)C\Delta H^2 + [(\alpha_B - \alpha_F)(1-p_e) + \alpha_F + \zeta]\Delta T \quad (2)$$

where C is the magnetostrictive parameter.

To test the simultaneous response of the sensor to electric current and temperature, the sensor head was introduced in a solenoid fed with dc current and heated by a resistor. The magnetic field in the center of the solenoid was 12.2 mT/A and had a variation of 0.2 mT/A along the axis of the sensor. The resistor length was longer than the sensor size and the temperature was measured in three different points (the center and the two ends) to keep the two specimens of the sensor in thermal equilibrium. The measured change of the Bragg wavelength induced by the magnetic field at different temperatures is shown in Fig. 3. We observe that for small magnetizing fields the Bragg wavelength has a quadratic variation with the applied field and the material approaches to saturation for large magnetic fields. By comparison of different curves we observe that wavelength shifts produced by temperature variations are comparable to changes produced by magnetostriction. To compensate temperature during dc current measurement, the grating mounted on the non magnetic alloy can be used as reference since this material is insensitive to magnetic fields as it is illustrated in Fig. 4.

Both materials have the same thermal expansion coefficient, therefore the difference between the wavelength reflected by the two gratings gives the magnetically generated strains in the fiber. The results are shown in Fig. 5 and represent the intrinsic thermal behavior of the magnetic material. For applied fields smaller than 4.7×10^4 A/m ($B < 60$ mtorr) the Bragg wavelength is linear with the density of energy of the magnetizing field. The sensitivity in this range is independent on the temperature and has an average value of $(2.31 \pm 0.05) \times 10^{-10}$ nm/(A^{2}m^{-2}). Substituting this value into equation (2) the material constant was found to be $C = (2.16 \pm 0.05) \times 10^{-13}$ A^{-2}·m^2. For large magnetic fields the saturation level decreases with increasing temperature, the maximum magnetostriction reached in this experiment for a field of 1.8×10^5 A/m ($B = 225$ mT) was $\Delta l/l = 0.93 \times 10^{-3}$ at 21.6°C, and it decreases to $\Delta l/l = 0.75 \times 10^{-3}$ at 73.7 °C.

The applied magnetic field in the linear range can be read directly from Fig. 5. Above the linear response ($H > 4.7 \times 10^4$ A/m) one can determine the magnetic field applied to the sensor at different temperatures combining the information of Fig. 5 with the temperature response provided by Fig. 2. Finally it must be pointed out the linear operating range of magnetostrictive materials can be extended over 1.5×10^5 A/m (188 mT) by applying a mechanical stress of about 50 MPa [9], [10].

III. Conclusion

A procedure based on fiber gratings for detection of temperature and static magnetic fields has been demonstrated. The device can be used as a temperature compensated sensor for dc currents or as an apparatus for characterizing the thermal behavior of magnetostrictive materials.

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