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Compensation of hysteresis in magnetic field sensors employing Fiber Bragg Grating and magneto-elastic materials

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ABSTRACT

The paper proposes a novel magnetic field sensor where a technique for hysteresis compensation is employed. The sensor integrates a magnetostrictive material with a Fiber Bragg Grating (FBG) strain sensor. Because of hysteresis and non-linear phenomena taking place in such materials, the sensor's performances may be sensibly reduced. To this aim, magneto-elastic material is accurately modelled in order to *compensate* hysteresis. In particular, the proposed approach allows to *embed* the compensation algorithm in the developed device, yielding to a more linear response of the sensor and to a reliable reconstruction of magnetic field. Results are shown and discussed.

1. Introduction

Magnetic sensors are useful to control or analyze functions in a large number of devices or physical processes. Therefore, they are widely spread in several fields of science and technology and are based on different physical processes (electromagnetic induction, Hall effect, superconductivity, magneto-resistance). Each of them has a specific application and, all together, can cover a great interval of detected fields (ranging from the order of 1 nT to the order of 1 T). Some of them are based on the behavior of materials having a physical parameter highly modified by a magnetic field (for example, the conductivity in giant magneto-resistive materials). This idea can be extended to other materials where a detectable physical quantity is strongly coupled to the magnetic field. To this end, magnetostrictive or, more in general, magneto-elastic materials, are suitable for the task, if reliable strain detection is available.

In last years, strain sensors based on optical fibers have been analyzed and developed. Their advantages include immunity to electromagnetic interference, compact design, reduced complexity, low cost of insulation construction [1]. Moreover, thanks to the small dimensions, they can be integrated in host structures to monitor location that are not accessible to other sensors (i.e. strain gages) [2,3]. Simultaneous multi-parameter measures can also be performed by these devices, able to work in very harsh conditions [4,5].

The idea to integrate a magnetostrictive material with optical fiber strain sensors to detect weak magnetic fields, was proposed in [6]. In this early paper an optical fiber with a magnetostrictive jacket was considered in such a way to exploit both magnetostrictive (controlled by the field, through the material) and elasto-optic effect shown by the fiber. Later, in [7], such idea was successfully implemented.

However, the sensitivity of the optical fiber based magnetic sensors can be considerably improved by using Fiber Bragg Gratings (FBGs). Indeed, among optics devices FBGs exhibit good features in terms of high sensitivity, resolution and bandwidth [5], that justified the great research effort in recent years [3]. Competitive costs, high multiplexing capability are further advantages of this class of devices.

In last decades, moreover, a great interest has been devoted to the development of materials with strong magneto-elastic coupling (Terfenol-D and Ni–Mn–Ga alloys) [8,9], and to devices employing them. Even if based on different physical behavior, they are both able to strongly deform in response to a magnetic field. In particular, Terfenol-D shows strains up to thousands of ppm, while Ni–Mn–Ga alloys can reach 10^5 ppm but need much higher fields. The integration of such strongly coupled magneto-elastic materials to a FBG-based sensor could yield to a passive, small size, magnetic field sensor.

Such idea has been recently developed and exploits a Terfenol-D alloy (generally a rod), as field–strain transducer, and a FBG strain sensor to measure the deformation due to magnetic field. The study and design of such devices have been tackled in sev-

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eral recent contribution. In [10], the analysis of a current sensor was considered, while a device obtained by the coupling of a FBG with a magnetostrictive material has been proposed to reduce sensor's temperature dependence, in [11]. In [12,15] a temperature-compensated current sensors was analyzed. Liu et al. proposed in [13] the analysis of a new temperature-compensated field sensor where materials with different magnetostriction and the same thermal expansion coefficient were employed. Moreover, Satpathi et al. [14] described the development of a current transducer, employing FBG and Terfenol-D material; a similar paper by Mora et al. [16], proposed an AC current and temperature sensor. In particular, the latter applied a simple memoryless model relying the strain response to the field in order to extract the current measurement; magnetostriction phenomena has been analyzed in [14] with more detail. There, it was observed that magnetostriction is a unipolar phenomena with hysteresis. Such characteristics yielded, as well known [17], to supply the rod with a bias current, in order to circumvent the former problem, and to pre-stress the rod in order to obtain a more linear response of the sample. In any case, however, any hysteresis phenomena has been disregarded. Finally, in [18] the Terfenol-D active material was replaced by a Ni–Mn–Ga alloy, and the performances of a new magnetic field sensors were studied.

Nevertheless, non-negligible *rate-independent* memory effects (i.e. hysteresis), impact the performance of such a device and could represent a severe drawback for its development. However, recently, hysteresis modelling has seen great progress [19,20], resulting in suitable techniques to model hysteresis. All such assessed knowledge, yielded to the development of a novel magnetic sensor, based on the integration of Fiber Bragg Grating and magnetostrictive material, where hysteresis compensation is performed by proper algorithms.

In the present paper the description of such a device is provided. Then, the discussion of hysteresis phenomena, intrinsic in any ferromagnetic and magneto-elastic material, is aimed to develop suitable algorithms for hysteresis compensation. It should be pointed out that hysteresis compensation, described in the following, approximately linearizes the sample's behavior and allows to increase, in the low frequency limit, the performances of the device (whatever is the employed active material, i.e. Terfenol, Ni–Mn–Ga alloys). Moreover, the ability to model and compensate hysteresis, could also be useful when the device works in a higher frequency range, as shown in [21,22], even if the issue of dynamic modelling of the sensor lies outside the scope of this study and could be tackled in a future work.

The positive effects of hysteresis compensation on the performances of the proposed device are experimentally demonstrated in the present paper through a wide number of measured data.

2. Fiber Bragg Gratings as strain sensors

A Fiber Bragg Grating is a periodic or semi-periodic permanent perturbation of the fiber core refractive index. So, when it is irradiated with a broadband optical source, a narrow band signal is reflected. The central wavelength of this signal, called Bragg wavelength λ_B, is related to the physical parameters of the grating, according to the following relationship [26]:

$$\lambda_B = 2n\Lambda, \quad (1)$$

where n is the effective refractive index of the fundamental mode propagating inside the fiber and Λ is the pitch of FBG. External causes, like strain, able to modify right hand terms of Eq. (1), cause a shift of the Bragg wavelength. In particular, when the FBG is subjected to strain fields, relative variations of λ_B induced by n or Λ changes can be obtained by differentiating Eq. (1) with respect to

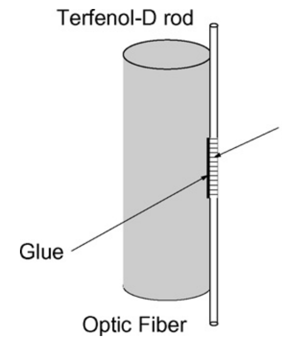

Fig. 1. Schematic description of the magnetic field sensor.

these two parameters, and applying the strain optic theory [27]. When only axial strain field significantly affects FBG response, the Bragg's wavelength relative shift is proportional to the applied longitudinal strain ε, according to the following equation:

$$\frac{\Delta\lambda_B}{\lambda_B} = \left(1 - n^2\,\frac{p_{12} - \nu(p_{11} + p_{12})}{2}\right)\varepsilon, \quad (2)$$

where p_{11}, p_{12} are two components of the elasto-optic matrix [27] and ν is the Poisson's ratio. Typical values of elasto-optic matrix elements and Poisson's ratio for standard optic fibers are: $p_{11} = 0.12$, $p_{12} = 0.27$ and $\nu = 0.17$ [27]. In this way, the Bragg's wavelength relative shift is proportional to the axial strain, or in other words, FBG converts strain into wavelength shifts [26], which is an absolute parameter, immune to optical power drifts along the measurement chain. In this work, the FBG is used as strain sensor and the Terfenol-D as magnetic field transducer. The device is built up by bonding FBG and magnetostrictive material together, as shown in Fig. 1. Magnetic field deforms the magnetostrictive rod, which actuates the FBG bonded on it, so modifying its Bragg wavelength.

2.1. Fiber Bragg Gratings interrogation technique

An important aspect of FBG-based sensors is the adequate detection of wavelength shifts [28–31]. Among various methods, interferometric techniques allow very sensitive and accurate measurements but complex and expensive configurations are required. Passive optical filtering techniques represent a good trade-off in terms of resolution, flexibility and costs [32]. The interrogation system used for the proposed magnetic sensor is passive and relies on a low cost technique based on optical filtering combined with broadband interrogation [26]. The block diagram of the interroga-

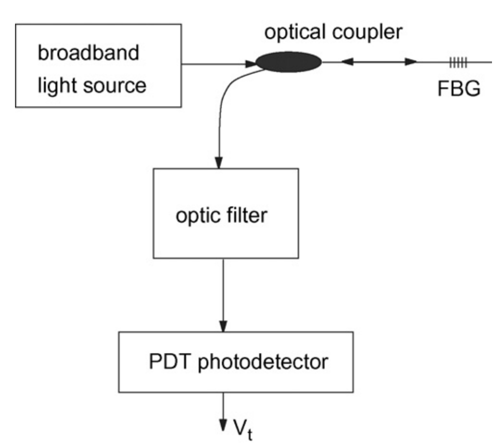

Fig. 2. Interrogation sensor system-block diagram.