Ferrule-top optical fibre sensor for the measurement of magnetic fields

M. Aerssens,[1,2] G. Gruca,[3] A. Gusarov,[2] V. Massaut,[2] P. Mégret,[1] D. Iannuzzi,[3] and M. Wuilpart[1]

[1] UMONS, Dept of Electromagnetism and Telecommunications, Blvd Dolez 31, 7000 Mons, BE.
[2] Belgian Nuclear Research Center SCK-CEN, Boeretang 200, 2400 Mol, BE.
[3] VU University, Dept of Physics and Astronomy, de Boelelaan 1081 Amsterdam, NL.

We present a magnetic field sensor based on a micromachined cantilever (with a N45 Neodynium magnet fixed on the upper end) carved on top of a ferruled fiber by means of a cost-effective picosecond-laser ablation. The interferometric readout of the ferrule-top (FT) sensor is based on a 1544 nm laser diode and an infrared photodetector. The FT calibration was obtained by moving the sensor along the principal axis of a stack of permanent toroidal magnets with a maximum magnetic field of 0.24T. The developed sensor has no hysteresis and presents a proportional relationship between the magnetic field and the interferometric cavity size.

Introduction

Ferrule-top cantilevers are a new generation of monolithic micromechanical sensors obtained by carving microstructures on the top of ferrule fibers. The movement of the structure can be monitored by means of laser light coupled into the fiber from the opposite end. They offer all the advantages of fiber optic sensors (e.g. small dimensions, remote sensing, insensitivity to electromagnetic noise, harsh environments resistance). Ferrule-top sensors can work in two modes. The static mode is based on recording elastic deflection of the cantilever and the dynamic mode relies on tracking changes in its mechanical properties (resonance frequency, quality factor). In this paper we present experimental results of the magnetic field measurement using a FT monitored in static mode.

Fabrication of ferrule-top sensors

The main idea is to use ferruled fibers as the building block of the ferrule-top device. The outer diameter of the ferrule is typically 1.8 mm. A standard single-mode optical fiber is inserted and glued into a pierced cylindrical ferrule made out of glass. The diameter of the piercing hole that passes through the ferrule along the axis of the cylinder is 127 µm. The single-mode fiber is glued into the ferrule so robustly that it is possible to carve a micromachined cantilever on top of the ferruled fiber by means of a cost-effective technique, namely picosecond-laser ablation. The different manufacturing steps are exhaustively described in [1] and illustrated in figure 1. The geometry of the sensor can be changed depending on the application. Nevertheless, in most of the cases the micromechanical element is a simple beam clamped on one side. To create from ferrule-top devices transducers to measure changes in the magnetic field, we have adhered to the upper end of the ferrule a thin slice of 200 µm of a N45 Neodynium magnet (alloy of neodymium, iron, and boron $Nd_2Fe_{14}B$) cut with a diamond wire-cutter according to the magnetic north-south axis.The pico second laser from Optec makes it possible through a graphical interface to control a linear translation table and define the regions subjected to laser ablation (Fig.2).

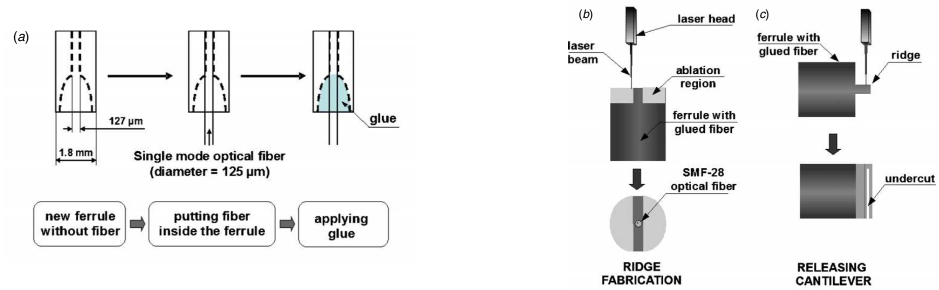

Figure 1: (a) Schematic view of a ferruled optical fiber; (b) and (c) milling steps in the fabrication of a ferrule-top cantilever [1]

Interferometric readout

The interferometric readout for the ferrule-top cantilever is based on a 1.544 µm laser diode and an infrared photodetector. The light of the laser beam, coupled to the cantilever through an optical circulator, is partially reflected at the fiber-to-air, air-to-cantilever and cantilever-to-air interfaces. The three backward propagating components interfere with each other, creating an interference pattern. The interference signal is then coupled to the photodiode through the circulator (Fig.3). As outlined by Iannuzzi et al. [2] and by Gruca et al. [1], the interference signal depends on the distance d between the fiber-to-air interface and the bottom surface of the cantilever. If multiple reflections from the cantilever are neglected, the output of the readout system may be described according to the following equation [2]:

$$W(d) = \left[1 + V.cos\left(\frac{4\pi d}{\lambda} + \varphi_0\right)\right] \quad (1)$$

where ϕ_0 is a constant phase shift that only depends on the geometry of the cantilever, λ the wavelength of the laser (1.544 µm) and V the fringe visibility. The midpoint interference signal W_0 and V are related to the output signals corresponding to maximum (W_-) and minimum (W_+) interference according to:

$$W_0 = \frac{W_+ + W_-}{2} \qquad V = \frac{W_+ - W_-}{W_+ + W_-} \quad (2)$$

Figure 2: (left) XY linear translation and Z Axis rotation stage controlled by the ps-ablation laser. (right) Top of the ferrule during the ablation process.

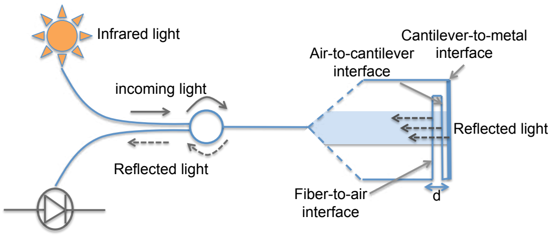

Figure 3: Schematic view of the readout setup. Dashed arrows represent the light reflected at the fiber-to-air, air-to-cantilever, and cantilever-to-metal interfaces.

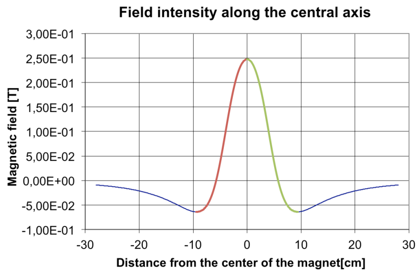

Figure 4: Magnetic field simulated along the axis of a stack of permanent toroidal magnets.

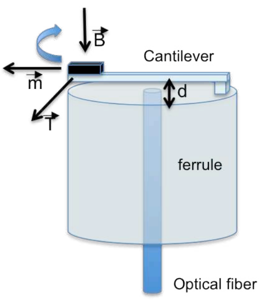

Figure 5: Magnet with a magnetic moment $\vec{m}$ on top of a cantilever submitted to a magnetic field $\vec{B}$. The magnet and the beam undergo a torque that changes the size of the cavity between the end of the optical fiber and the bottom of the cantilever.

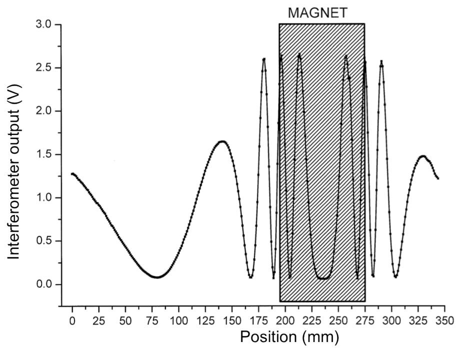

Figure 6: Output voltage measured by the interferometric readout when the sensor moved along the axis of a stack of permanent toroidal magnets.

Measurements and sensor calibration

The set-up consists in a ferrule-top sensor mounted on the end of a non-metallic arm that can move inside a stack of permanent toroidal magnets with a maximum magnetic field of $0.24T$ with a position measured to the hundredth of a millimeter (Fig.4). When the sensor is moved along the axis of the magnet, the interaction between the magnetic moment $\vec{m}$ and the magnetic field $\vec{B}$ gives rise to a torque that changes the size of the cavity between the end of the optical fiber and the bottom of the cantilever (Fig.5). Based on Eq.1, we deduce that the interferometric output changes from minimum to maximum and vice versa when d undergoes a change of $\lambda/4 = 387.5$nm. The evolution of the interferometer readout (Fig.6) gives approximately a modification of the cavity size d of 2712nm for a magnetic field B $\in$ [-0.06T 0.24T].

If we represent the interferometer output according to the magnetic field (combination of Fig.4 and Fig.6) for the areas where the magnetic field is respectively monotically increasing (red curve on Fig.4) and decreasing (green curve on Fig.4), we obtained two similar calibration curves for [-0.06T 0.24T] (Fig.7) showing that our sensor is not subjected to any hysteresis. Assuming that the magnetic field applied to the sensor is low

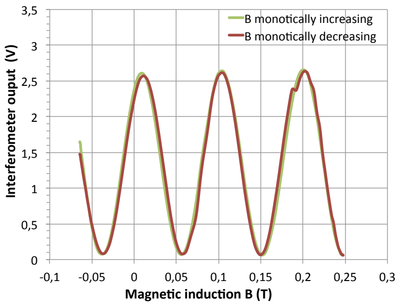

Figure 7: Evolution of the interferometer output for the monotically increasing (red curve) and the monotically decreasing (green curve) area of the magnetic field.

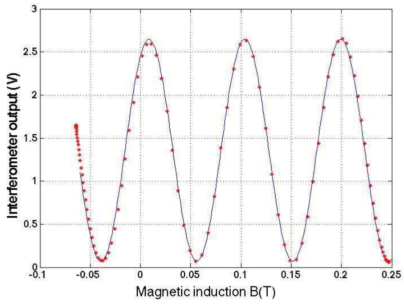

Figure 8: Fitting with a sine function of the monotically increasing area of the magnetic field.

enough to generate a linear deformation of the cantilever, Eq.1 shows that the evolution of the interferometer as a function of the magnetic field should follow a sinusoid. The assumption of proportionality between the magnetic field and the length of the sensor cavity is verified for B $\in$ [-0.06T 0.24T] since we observe a good matching between the output of the interferometer and the sine function that best fits in the least-squares sense (Fig.8).

$$y = 1.36 + 1.29 * sin\left(\frac{B - 0.08}{0.048}\right) \qquad (3)$$

Conclusion

In this paper we use a ferrule top sensor with a small neodymium magnet glued on top of the ferrule in conjunction with an interferometer system to measure the magnetic field. To prevent the overheating of the sensor inherent with an electromagnet, we use a stack of toroidal permanent magnets to generate a stable magnetic field. The sensor was moved along the principal axis of the magnet and we recorded via the output of the interferometer the static bending of the cantilever. Experimental results demonstrate on one hand that the sensor has no hysteresis in the range [-0.06T 0.24T]. On the other hand, the size modification of the interferometric cavity d is proportional to the amplitude of the magnetic field, meaning that the evolution of the interferometric output as a function of magnetic field is sinusoidal.

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