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DC and AC linear magnetic field sensor based on glass coated amorphous microwires with Giant Magnetoimpedance

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ABSTRACT

Giant Magnetoimpedance (GMI) effect has been studied in amorphous glass-coated microwires of composition $(Fe_6Co_{94})_{72.5}Si_{12.5}B_{15}$. The impedance of a 1.5 cm length sample has been characterized by using constant AC currents in the range of 400 μA–4 mA at frequencies from 7 to 15 MHz and DC magnetic fields from −900 to 900 A/m. Double peak responses have been obtained, showing GMI ratios up to 107%. A linear magnetic field sensor for DC and AC field has been designed, using two microwires connected in series with a magnetic bias of 400 A/m with opposite direction in each microwire in order to obtain a linear response from $\pm 70\ (\mathrm{A/m})_{rms}$ for AC magnetic field, and ±100 A/m for DC magnetic field. A closed loop feedback circuit has been implemented to extend the linear range to ±1 kA/m for DC magnetic field.

1. Introduction

Glass coated amorphous microwires have attracted much attention and they have been intensively studied during the last two decades. Since the Giant Magnetoimpedance (GMI) was discovered in 1994 [1,2], many theoretical models have been developed to explain this phenomenon [3–6]. The magnetization processes in microwires showing the GMI effect have been studied [7,8] and many works dealing with technological applications were reported because of the outstanding magnetic properties [9–15] which makes them useful as high sensitivity magnetic sensors [16–20], biosensors [17,19,21,22], current sensors [23] and magnetometers [24]. It is remarkable the contribution of Mohri et al. in the development of electronic circuits for GMI sensors [16,20]. These previous works reported GMI sensors including signal conditioning. Such sensors were excited with a pulsed voltage, leading to changes in the current amplitude which modifies de characterized GMI response which is done at constant current amplitude (note that the GMI ratio and the peak of the GMI response depend on the current). Here we present a different approach where the GMI sensor is excited with constant current amplitude. We also apply a bias field in order to work on the field over the GMI peak, where the hysteresis is negligible. GMI in amorphous microwires has been also studied at microwave frequencies [15,25], and also the absorptive properties due to the phenomenon of Ferromagnetic Resonance (FMR) [26–29], or the recently experimental demonstration of its behavior as a metamaterial due to the coexistence of negative permittivity and permeability in the frequency region between FMR and Ferromagnetic Antiresonance (FMAR) [30]. This structure allows the possibility of modifying a pass band between FMR and FMAR through an external magnetic field [30] or with a current though the microwire [31], even modulating a microwave signal with an AC current.

GMI has been studied in several structures like magnetic ribbons, wires and microwires [32,33]. The GMI phenomenon is due to the skin effect in magnetic conductors. When an external magnetic field interacts with the conductor, the permeability is highly increased in such a manner that the skin depth is reduced. The impedance of a magnetic conductor with radius r and an AC driving current is given by [4]:

$$Z = R_{dc}(kr)\frac{J_o(kr)}{2J_1(kr)},$$

where R_{dc} is the DC resistance and J_o and J_1 are the Bessel functions of zeroth and first order, respectively. In addition, $k = (1+j)/\delta$, where δ is the skin depth given by

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu_\phi}},$$

σ being the electrical conductivity, $\mu_\varnothing$ the magnetic circular permeability and f the frequency of the AC current.

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The high value of μ in soft magnetic materials will cause that the skin effect appears at lower frequencies than nonmagnetic metals with the same conductivity. In addition, its strong dependence with the external magnetic field will originate large impedance variations. In ferromagnetic materials the AC permeability is not isotropic and depends on the orientation of the AC and DC magnetic fields and the sample anisotropies. Concretely it is the effective transverse permeability μ_t which is involved in GMI, also called circular permeability μ_ϕ in the case of cylindrical geometry.

The impedance variations are usually quantified through the GMI ratio, which is defined as:

$$\frac{\Delta Z}{Z}(H) = \frac{|Z(H)| - |Z(H_{max})|}{|Z(H_{max})|}$$

GMI ratios can typically exceed the value of 100%, some works reporting values up to 600% [21]. Due to these huge impedance variations, which occur in a narrow range of magnetic fields, microwires can be employed to design highly sensitive magnetic sensors. However the main drawback associated to this phenomenon consists of the non-linear behavior of the samples.

This work is focused on the GMI phenomenon in glass coated amorphous microwires whose diameters take typical values around 10 µm. Firstly these microwires have been characterized in a system designed to measure the impedance of magnetic samples under different magnetic fields and excitation currents. Then, we present the design and test of a DC and AC linear magnetic field sensor intended to measure fields in the range $H_{dc} = \pm 100$ A/m and $H_{ac,RMS} = 70$ A/m with a frequency range up to 50 kHz. Finally, we propose an upgrade of the initial sensor which allows to extent the measurable range of DC fields up to 1 kA/m with a remarkable linearity.

2. GMI measurement procedure

As exposed, the GMI phenomenon is a consequence of the skin depth, which depends on the frequency and the circular permeability of the magnetic sample. This last parameter in turn depends on the amplitude and frequency of the electric current flowing through the sample, as well as the presence of an external magnetic field. Therefore the experimental characterization of the GMI phenomenon relies in the implementation of an automated system capable of controlling these three parameters. In this sense a measurement setup intended to measure the impedance of the samples under different conditions has been developed.

Fig. 1 shows the equipment included in the system. Three perpendicular Helmholtz coils are used in order to compensate the Earth's magnetic field while an additional coil is employed to generate the magnetic field which excites the samples. The DC current feeding this latter coil is provided through a KEPCO BOP 50-8D current source and the amplitude of the magnetic field applied to the samples is measured with a FW Bell 7010 Gaussmeter. On the other hand, the current passing through the microwire consists of a sinusoidal wave with fixed current amplitude which is generated with an Agilent 33120 function generator. Finally, the electrical parameters are acquired through a Tektronix TDS3012B digital oscilloscope. All these devices are connected with a GPIB bus to a computer.

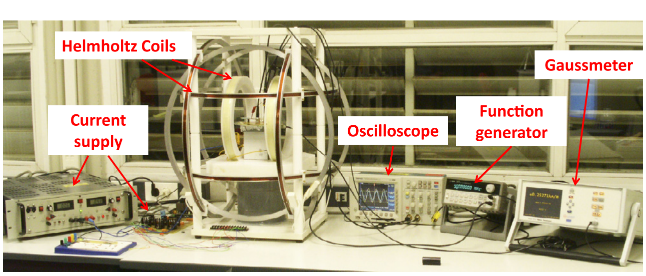

Fig. 1. GMI measurement setup containing the equipment required to characterize magnetic samples.

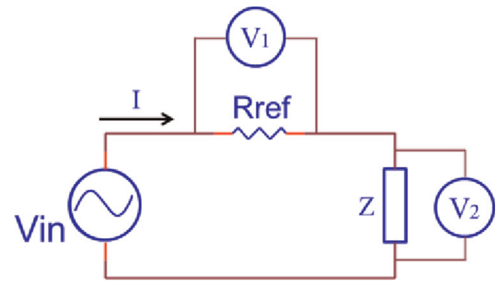

Fig. 2. Circuit employed to determine the impedance of the samples.

The impedance of the microwires is obtained through the scheme represented in Fig. 2. It is based on a non-inductive precision resistor R_{ref} in series with the sample. Thus the current through the sample can be determined by measuring the voltage drop across such resistor with a differential probe. Then the voltage drop across the sample is directly obtained, in such a manner that the unknown impedance is calculated as $Z = V_2 R_{ref} / V_1$. Note that this process is performed by setting a current with constant amplitude. Since the function generator cannot provide constant current amplitude, the computer controlling the system sets the voltage V_{in} according to the expected value of V_1 for the desired measurement current amplitude.

3. Experimental results

The amorphous microwires considered in this work have $(Fe_6Co_{94})_{72.5}Si_{12.5}B_{15}$ composition, which is characterized by near zero magnetostriction ($\lambda_s = -10^{-7}$) [10]. The microwires used for the sensor are 1.5 cm long, and have a ferromagnetic core with 4 µm of diameter surrounded with a glass coating of 5 µm (see Fig. 3). The Co-rich composition tied with its null magnetostriction constant creates a circular magnetic domain structure that shows GMI, characterized by a double peak response [18].

The measures were performed for a microwire with a length of 1.5 cm under static magnetic fields in the range ± 900 A/m, frequencies from 7 to 15 MHz and currents up to 4 mA_p. Fig. 4 shows the impedance modulus of the increasing branch of the GMI curve for different frequencies and a constant current of 1 mA_p. As expected, it is observed a double peak behavior due to the circular anisotropy field, H_K, characterizing the employed microwires. Such peaks appear

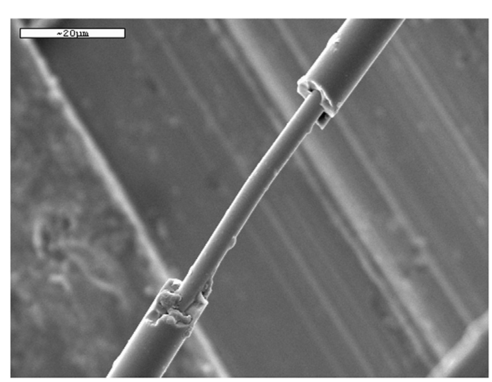

Fig. 3. SEM image of a magnetic microwire. It is based on a magnetic core which is covered with a glass coating.