Magnetic field transducers based on the phase characteristics of GMI sensors and aimed at biomedical applications

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Abstract — **For the last four years the Laboratory of Biometrology of PUC-Rio has been working in the development of magnetic field transducers to be used in biomedical applications – especially in the three-dimensional localization of needles inserted in the human body and in the measurment of arterial pulse waves. While previous investigations were based on the behavior of the magnitude of the impedance of Giant Magnetoimpedance (GMI) ribbon-shaped sensors, this manuscript presents the preliminary results of a new research that considers the changes in the phase characteristics of GMI sensors due to varying low-intensity magnetic fields. In spite of being less explored in the literature, the work carried out so far indicates that the sensitivity of the phase can lead to more promising results than the ones already obtained with transducers based on the variation of the impedance magnitude. By means of examples showing that the sensitivity of the phase is affected by parameters (amplitude, frequency and DC level) of the AC biasing current that flows throught the sensor, this manuscript discusses how an ideal stimulation condition was derived in order to obtain more sensitive transducers. It is also examined the influence of the ribbon length in the sensitivity. A new conditioning electronic circuit – responsible for the excitation and measurement of the GMI sensor, and designed to work in the 100kHz to 5Mhz range – has been developed and is presented in the manuscript. Simulation studies of the complete transducer, including the conditioning circuit and based on data obtained from measured curves, have shown that an improvement of 10 to 100 times can be expected when compared to the sensitivity of previous magnitude-based transducers.**

Keywords — **Metrology, Biometrology, Giant Magnetoimpedance, Phase Characteristics, Biomedical Transducer.**

I. Introduction

A. Historical context

The department of Metrology for Quality and Innovation (Post-MQI) of PUC-Rio, through the research line in Biometrology and in partnership with the department of Physics of the Federal University of Pernambuco (UFPE), is carrying out studies seeking the implementation of prototypes of magnetometers based in the Giant Magnetoimpedance (GMI) phenomenon [1-2].

The importance of GMI in the world's scientific scenery has been increasing, and several laboratories are accomplishing promising researches in several application areas. A recent example was the concession of the 2007 Nobel Award in Physics to the researchers Albert Fert and Peter Grünberg, who discovered the giant magneto-resistance, GMR [3,4].

The Giant Magnetoimpedance effect started to be studied intensely in the decade of 90. The first results obtained in such studies were interpreted as a variation of the Giant Magnetoresistance effect (GMR), whose experimental behavior is examined with the application of a continuous current and in the presence of a continuous magnetic field. The GMR effect only considers the variation of the resistance, and the phenomenon is explained by the electrons motion change when we act on their spin through the orientation of a magnetization [3]. However, experiments accomplished with samples of amorphous ferromagnetic alloys, using alternating current, have shown a variation of the resistive part as well as of the reactive part with respect both to the external magnetic field and to the frequency of the applied current. Thence comes the name GMI.

B. GMI effect

We focus on a particular case of GMI named Longitudinal Magnetoimpedance (LMI). The phenomenon of LMI is induced through the application of an alternating current (I) along the length of a ribbon (or wire), which is submitted to an external magnetic field ($\vec{H}$) parallel to it. The potential difference (V) is then measured between the extremities of the ribbon, as shown in Figure 1.

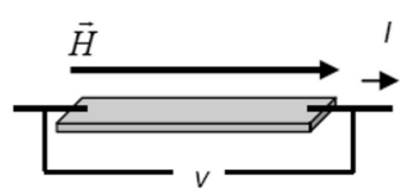

Fig. 1: Typical GMI measurement.

Chwee Teck Lim, James C.H. Goh (Eds.): ICBME 2008, Proceedings 23, pp. 652–656, 2009
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Using the phasorial description of the AC tension and current, as well as arbitrating the phase of the current (ϕ_I) as zero, the impedance of the sample can be calculated as:

$$Z=\frac{|V|e^{j\phi_V}}{|I|e^{j\phi_I}}=\frac{|V|}{|I|}e^{j\phi}=|Z|e^{j\phi} \tag{1}$$

Thus, the complex impedance (Z) is defined by two components, a real one and imaginary one:

$$Z=R+jX\,, \tag{2}$$

where

$$R=|Z|\cos\phi \;\text{ and }\; X=|Z|\sin\phi \tag{3}$$

The GMI effect is actually a result of the skin depth dependency with the magnetic permeability, which varies not only with the external magnetic field that is applied to the sample, but also with the frequency and intensity of the current that passes through it. Then, generically, in agreement with the literature [5-6], we can define:

$$Z=(1-i)\frac{L}{2\omega\sigma\delta}\frac{1}{1-e^{-(1-i)t/2\delta}}\text{ , and} \tag{4}$$

$$\delta=\frac{c}{2\pi}\sqrt{\frac{1}{2\omega\mu\sigma}}\,, \tag{5}$$

where L is the length and t is thickness of the ribbon, ω is the frequency of the current and σ is the conductivity of the material.

A. Previous Works

The Laboratory of Biometrology of PUC-Rio has developed, in the recent past, some magnetic field transducers for biomedical applications, all based on the magnitude characteristics of the GMI phenomenon.

As a matter of fact, most of the studies accomplished in the field of GMI has been based in the magnitude characteristics of the samples, being rare those that consider its phase characteristics. Even the most used figure for determination of the GMI percentile variation - as a function of the applied magnetic field - takes into account just the magnitude [5-6]:

$$GMI(\%)=\left[\frac{|Z(H)|-|Z(H_{max})|}{|Z(H_{max})|}\right]10^2\,, \tag{6}$$

As examples of transducers developed at PUC-Rio, which are based on the magnitude variation of the GMI effect and uses GMI ribbons as sensor elements, it can be mentioned the transducer for localization of needles inserted in the human body shown in Fig. 2 (which sensitivity was 12V/Oe), and the transducer for measurement of arterial pulse waves shown in Fig. 3 (which sensitivity was 1mV/Pa) [1-2, 7-8].

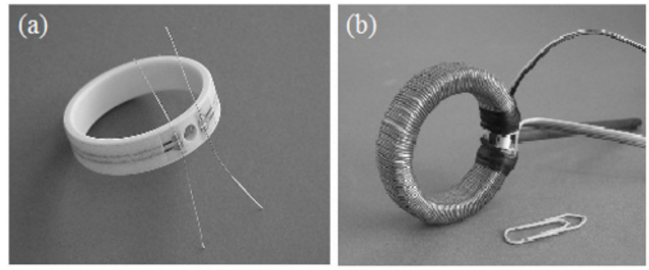

Fig. 2: (a) Partial ring shaped prototype with GMI ribbons fastened; (b) Complete prototype with the excitation coils.

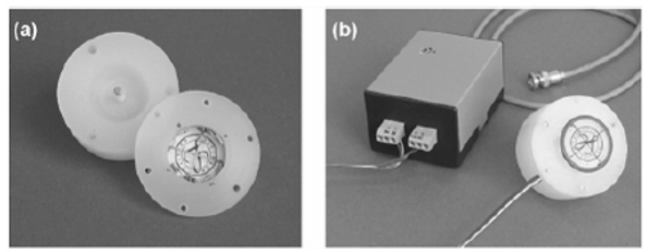

Fig. 3: (a) Opened prototype without the electronic circuit; (b) Complete prototype.

This paper presents the improvements introduced in the foregoing transducers when the phase characteristics of GMI samples started to be considered in place of its magnitude.

II. Experimental research

A. Phase and Magnitude Characterization

Some initial studies have examined the effect of the frequency and DC level of the excitation current on the sensitivity of the ribbons. All those parameters, as well as the length of the ribbon, affect the magnitude and phase sensitivity in a significant and different way.

Such studies lead to the conclusion that the ribbons presented a maximum sensitivity for DC currents around 80mA, independently of their length or of the AC current frequency. Measurements were accomplished with DC currents of 0mA, 20mA, 40mA, 60mA and 80mA. Due to technical limitations, and to the difficulties imposed by its microelectronic implementation, the sensitivity for higher current values was not tested, but the results should continue to get better.