Perspectives in Giant Magnetoimpedance Magnetometry

D. Menard, D. Seddaoui, L. G. C. Melo, A. Yelon, Basile Dufay, Sébastien Saez, Christophe Dolabdjian

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D. Ménard[1,*], D. Seddaoui[1], L. G. C. Melo[1], A. Yelon[1], B. Dufay[2], S. Saez[2], and C. Dolabdjian[2]

[1] *École Polytechnique de Montréal, Département de génie physique and Regroupement québécois des matériaux de pointe, CP 6079, succ. Centre-ville, Montréal, Que., Canada H3C 3A7*

[2] *GREYC (CNRS–UMR6072), ENSICAEN and Université de Caen Basse Normandie, 6 Bd. du Maréchal Juin, France 14050 Caen Cedex*

Approximate expressions are obtained for the sensitivity of a GMI wire. The optimal conditions for high sensitivity are discussed in terms of material and external parameters, such as *dc* field, *dc* current bias, driving current amplitude and frequency. We show that the systematic reduction of the anisotropy field is not necessarily the best approach to increasing the material sensitivity.

Keywords: Giant Magnetoimpedance, Material Optimization, Magnetometer.

1. INTRODUCTION

The design of highly sensitive magnetometers based on the giant magnetoimpedance (GMI) effect requires reliable models for the electrical impedance response of soft magnetic metals as a function of applied magnetic field and of driving current (frequency and magnitude). Such models are well-established for the linear regime, for which the response is independent of the driving current magnitude.[1] It also requires models for the noise of the device, which ultimately limits the performance of the magnetometer. Such models are now being developed.[2,3]

The impedance ratio, $\Delta Z/Z$, has been widely used as a figure of merit, to highlight the potential of the GMI effect for magnetometry and to compare the performance of different GMI sensing elements. Upon its discovery in the mid 90's, the GMI effect was contrasted with the giant magnetoresistance effect (GMR), showing a higher and more sensitive impedance ratio than those of GMR elements. Indeed, for GMR elements, which are often used in a bridge configuration, the resistance ratio, $\Delta R/R$, is directly relevant to the output of the sensors. However, this is not necessarily the case for GMI, for which a bridge configuration does not appear to be the best design. It is also important to realize that a higher $\Delta Z/Z$ ratio does not necessarily correspond to a higher sensitivity. This is illustrated in Figure 1, where we compare the GMI response of a magnetic wire for two sets of experimental parameters. We believe that the value of the $\Delta Z/Z$ parameter, which provides no direct information as to impedance variation as a function of applied field, has been over-emphasized as a meaningful metric for several GMI applications.

Here we consider what we believe to be the greatest challenge in GMI magnetometry: the problem of making highly sensitive magnetometers (measuring small fields or changes in fields). We take the point of view that the sensitivity is more relevant than the $\Delta Z/Z$ ratio, for such applications. A simplified approach is proposed for analysis of the intrinsic sensitivity of a GMI wire, in units of V/T, as will be defined in Eq. (1). This corresponds to the slope of the GMI response, in units of Ω/T (Fig. 1), multiplied by the amplitude of the driving current. We assume that the GMI element is operated in a field-locked loop configuration, providing a bucking field which keeps the element in a state of optimal sensitivity. Our goal is to highlight the relevant combination of magnetic material parameters and operating conditions which optimize the sensitivity.

2. MODEL OF GMI SENSITIVITY

Modeling of GMI response involves two steps: obtaining the quasi-static magnetic structure of the element as a function of the applied field, and then, simultaneously solving Maxwell's equations and the equation of motion for the magnetization for the given magnetic structure.

*Corresponding author; E-mail: david.menard@polymtl.ca

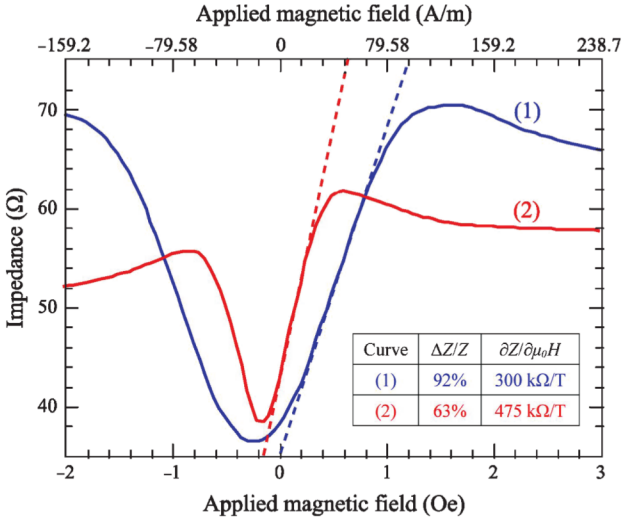

Fig. 1. Comparison between the modulus of the impedance as a function of the applied longitudinal field for a representative Co-rich amorphous wire operating at: (1) 30 MHz with a 10 mA *dc* bias current and (2) 3 MHz with a 2 mA *dc* bias current.

The distinctions between different models reported in the literature come essentially from the starting assumptions as to the magnetic structure (e.g., presence or absence of a domain structure) and the degree of approximation used in the solution of the subsequent equations (e.g., quasi-static, local approximation, rigorous approach).[4] Our model is based on a single domain structure, solved using the rigorous approach in the linear regime.[5] The justification for such a choice is presented below, in the discussion.

Optimal conditions for GMI operation, in terms of intrinsic signal-to-noise ratio, have been determined from existing noise models in the linear regime.[2] The theoretical equivalent magnetic noise is estimated to be well below what has been achieved experimentally, so far. In order to reach these theoretical noise levels, the sensitivity must be increased.[3] Figure 2 shows the typical, two peaks, response of a GMI wire operating in the linear regime. The maximum slope of the response, corresponding to the solid straight line, may be roughly approximated by the ratio Z_{pk}/H_{pk}, where Z_{pk} and H_{pk} are the impedance maximum and its field position, or, alternatively, by the ratio of impedance variation over field variation between the origin and the peak, as illustrated by dotted lines in the figure. Obviously, these approximations are imperfect. Comparison, with a large ensemble of experimental data, shows that the first approximation systematically overestimates the sensitivity whereas the second underestimates it. Nevertheless, both approximations remain roughly proportional to the real slope for a variety of experimental conditions, thus providing meaningful approximate expressions for the analysis of the sensitivity. In this work, we adopt the first approximation, so that an average sensitivity

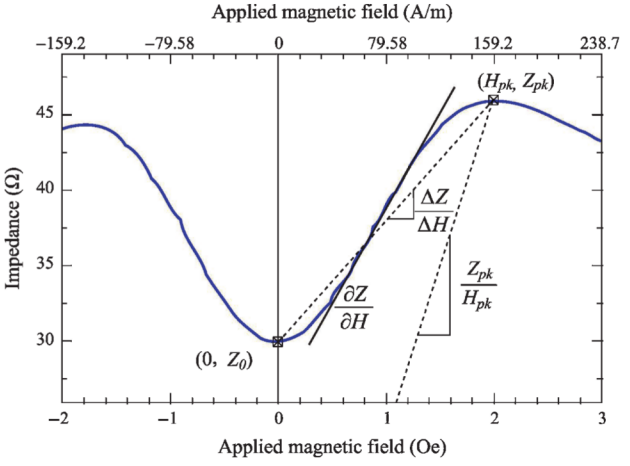

Fig. 2. Modulus of the impedance of a representative Co-rich amorphous wire as a function of the applied longitudinal field. The measurement has been performed at 10 MHz. The black solid straight line represents the maximum slope. The dotted lines are two alternative approximations for the slope. Note that $Z = 0$ is outside the figure.

$S(V/T)$ may be estimated from

$$S = \frac{I_{\rm ac}}{\mu_0}\frac{\partial Z}{\partial H_0} \approx \frac{Z_{pk}}{\mu_0 H_{pk}} I_{\rm ac} \tag{1}$$

where H_0 is the longitudinal applied field, and $I_{\rm ac}$ is the amplitude of the driving current. As usual, in GMI studies, the impedance in Eq. (1) is loosely defined as the ratio of the voltage across the wire to the driving current amplitude (this is not rigorously correct outside the linear regime).

Let us assume an ideal monodomain soft magnetic wire, of length l, operating in the strong-skin-effect regime, with a perfectly circumferential anisotropy within the skin depth region. The maximum impedance is given by

$$Z_{pk} \approx \frac{aR_{dc}}{2\delta_{\rm min}} = \frac{\ell}{2\pi a\sigma\delta_{\rm min}} \tag{2}$$

where σ is the conductivity, $\delta_{\rm min}$ is the minimum skin depth and a is the wire radius, with $a \gg \delta_{\rm min}$. Below a certain crossover frequency, the minimum skin depth is fundamentally limited by the exchange-conductivity effect, and depends upon the frequency, following the expression[6]

$$\delta_{\rm min} \approx \left(\frac{A}{\mu_0^2 M_{\rm s}^2 \sigma\omega}\right)^{1/4} \tag{3}$$

where A is the exchange stiffness constant, $M_{\rm s}$ the saturation magnetization and ω the angular frequency of the driving current. Above the crossover, it is limited by the phenomenological Gilbert damping parameter, α, and is independent of frequency, that is Ref. [6]

$$\delta_{\rm min} \approx \left(\frac{\alpha}{\mu_0^2 \gamma M_{\rm s}\sigma}\right)^{1/2} \tag{4}$$

where γ is the gyromagnetic ratio. The crossover between the two regimes occurs at an angular frequency

$$\omega_{\rm c} = \frac{\mu_0^2\gamma^2\sigma A}{\alpha^2} \tag{5}$$

which corresponds to a few hundreds of MHz for typical wire parameters.

It is observed, from GMI measurements, that there is a critical driving current above which the sensitivity starts to decrease. In order to highlight the effect of material parameters on the sensitivity, it is useful to express this optimal driving current in terms of a critical surface magnetic field (discussed below), that is, $(I_{ac})_{opt} = 2\pi a H_c$, the sensitivity in V/T per unit length of the wire will now be given by

$$\frac{S}{\ell} \approx \left(\frac{M_s^2 \omega}{\mu_0^2 \sigma^3 A}\right)^{1/4} \left[\frac{H_c(\omega)}{H_{pk}(\omega)}\right] \quad (\omega \leq \omega_c) \tag{6}$$

or by

$$\frac{S}{\ell} \approx \left(\frac{\gamma M_s}{\sigma \alpha}\right)^{1/2} \left[\frac{H_c(\omega)}{H_{pk}(\omega)}\right] \quad (\omega \geq \omega_c) \tag{7}$$

depending upon the driving current frequency. Note that H_c and H_{pk} are frequency dependent. In the quasi-static regime they are both equal to the anisotropy field H_k, so that the field ratio on the right hand side of Eqs. (6) and (7) is unity. At higher frequency, the peak position H_{pk} increases, in agreement with the Kittel ferromagnetic resonance condition.[4–6] For typical microwire parameters, a field shift, on the order of 1% or less is observed around 25 MHz or below, whereas at 250 MHz H_{pk} is approximately double its quasi-static value. GMI experiments also show that the value of H_c increases with driving current frequency, but a formal expression for this dependence is not available at present.

3. JUSTIFICATION OF THE MODEL

Let us first observe that a natural figure of merit for the sensitivity is S/l in V/T per unit length of the GMI element. This clearly establishes the trade-off between sensitivity and spatial resolution. It might seem surprising not to see any explicit dependence of the sensitivity on the wire radius. In fact, this dependence is hidden within the assumption that we are operating in the strong skin effect regime. Thus, the minimum conductivity which can be considered in Eqs. (6) and (7) is limited by the wire radius.

Before we draw any further conclusions based on Eqs. (6) and (7), we must critically review the assumptions used in their derivation. It is well-known that the presence of domains in a magnetic sample can result in a very high permeability in some circumstances.[1] In this work, and previous work from our groups, we chose to neglect the possible presence of any domain structure, for several reasons. First, as has been shown by models and experiments, a domain structure is not strictly required for high GMI sensitivity.[4–7] Second, at frequencies where we usually operate our GMI element (above 10 MHz) the possible contribution of domain movement to the total permeability is not likely to be significant. Further, in ultra-soft magnetic structures, the domains are difficult to predict or to control, yielding potential reliability, stability and reproducibility problems. In fact, the presence of domains is likely to lead to additional magnetic noise, as compared with the single domain situation. Finally, we believe that we can avoid most of the potential problems due to domains, eliminating them, by applying sufficient *DC* bias current.[2, 3]

Another important assumption is that the GMI element operates in the linear regime (the model is based on the linearized equation of motion for the magnetization). It is not immediately obvious that the optimal driving current is below the value at which significant non-linear response appears. This issue is particularly important, considering that all current dynamical models of GMI response are linear, whereas a significant portion of the measurements reported in the literature are performed in highly non-linear conditions (for typical GMI wires operating below 10 MHz, only a few mA are required to drive it into the non-linear regime.[8] Experimentally, it is observed that as the current increases, the characteristic double-peak response gradually evolves into a single peak response, with a corresponding reduction of sensitivity in the low-field regime. We have recently developed a numerical calculation of the GMI response for the non-linear regime sensitivity,[8] which reproduces this behavior. Both the experiment and the calculation, for typical wires used in GMI experiment, show that the driving current, above which the sensitivity starts to decrease, is located not far above the crossover at which non-linear behavior is first observed. In this limit, the use of a linear model seems reasonable.

Finally, one might question the relevance of treating an ideal wire with a perfect circumferential anisotropy. As was shown by Kraus,[6] slight deviations of the anisotropy, from the ideal circumferential case, result in a significant decrease of the GMI amplitude. In such conditions, an $\omega^{1/2}$ dependence of the GMI amplitude is expected, rather than the $\omega^{1/4}$ predicted by Eq. (6).[6] Nevertheless, the general trend remains the same, that is, both the amplitude and the peak position increase with frequency, at least up to a frequency, above which the amplitude remains approximately constant and, therefore, the sensitivity starts to decrease.

An important factor in determining the optimal frequency for the highest sensitivity is the frequency dependence of the driving-current-related critical field H_c. Experiment shows that H_c, which is approximately equal to the anisotropy field H_k at low frequency, eventually increases with ω, faster than H_{pk}. The non-linear model, which also reproduces both these trends,[8] allows us to anticipate that, for relatively high frequency (typically several tens of MHz) H_c corresponds to unrealistic driving current amplitudes at which the GMI element would be damaged. Practically, we do not approach that limit, so that

the optimal driving current will correspond to the onset of non-linear behavior at lower frequency or be limited by the power of the source at higher frequency.

4. PERSPECTIVES FOR HIGH SENSITIVITY

In terms of material parameters, provided that driving current and frequencies are optimized, both Eqs. (6) and (7) point towards the use of a M_s/σ ratio as high as possible. It is not easy to significantly increase M_s, as we are usually working with relatively strong ferromagnets. The conductivity can be decreased more easily, yet it must remain large enough in order for the sample to be in the strong skin effect regime. The above considerations also point towards the use of frequencies as high as possible, at the crossover frequency ω_c or at the frequency at which H_{pk} begins to increase rapidly, if it is lower than ω_c. However, the lower conductivity also implies a lower crossover frequency, given by Eq. (5), which means that the optimum is likely to be at ω_c, with a sensitivity given by Eq. (7). Decreasing the conductivity will also have adverse effects on electronic noise or on impedance matching, which have not been considered here.

Assuming that we have an optimal combination M_s, σ, a, and that we are working at the optimal conditions of field and frequency, the limiting factor is α, which is related to the magnetic losses. Although α is conventionally a material constant related to the intrinsic magnetic damping, here we may consider it loosely as a field and frequency dependent phenomenological damping term which may also include the inhomogeneous damping due to the imperfections of the material. The inhomogeneity of the anisotropy (direction and intensity), which is related to fluctuations of internal stresses, defects and chemical composition and to surface roughness, among others, appears to be the main limiting factor preventing us from achieving higher sensitivity.

The above simplified analysis is based on the realisation that the sensitivity of current state-of-the-art GMI sensors are limited by the sensitivity of their GMI elements.[3] It is meant to suggest design rules and directions of improvement. Some aspects of the problem have been neglected. Other constraints on the driving current amplitude and frequency, and on the material parameters imposed by the conditioning electronics, will be considered elsewhere.

5. CONCLUSIONS

Approximate expressions have been obtained for the sensitivity of a GMI wire in units of volt per tesla per unit length of the wire. Based on the proposed analysis, the optimal conditions for a highly sensitive GMI element are as follows. A monodomain wire, properly biased by a *dc* field and *dc* current, will have an optimal driving current amplitude and frequency which maximize the sensitivity. The material should have a magnetization to conductivity ratio (M_s/σ) as high as possible, limited by the radius of the wire. The homogeneity of the wire, particularly the quality of the surface, is extremely important to achieve a highly homogeneous well-defined anisotropy, which is crucial for a high sensitivity.

Another important conclusion to draw from the analysis is that the systematic reduction of the anisotropy field is not necessarily the best approach to increasing the material sensitivity. A very small anisotropy field will limit the amplitude of the driving current above which the sensitivity (in V/T) starts to decrease. It is also likely to produce an inhomogeneous magnetic structure, thus decreasing the GMI amplitude. In the best possible condition, the optimal frequency will generally be the crossover frequency, given by Eq. (5), which should be high enough that it does not impose any limitations on the driving current amplitude.

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