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Large nonlinear magnetoimpedance in amorphous 
$\text{Co}_{80.89}\text{Fe}_{4.38}\text{Si}_{8.69}\text{B}_{1.52}\text{Nb}_{4.52}$ fibers

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Fourier analysis of the nonlinear response of the impedance signal of amorphous $\text{Co}_{80.89}\text{Fe}_{4.38}\text{Si}_{8.69}\text{B}_{1.52}\text{Nb}_{4.52}$ fibers is presented. The harmonic components of the voltage signal present a strong asymmetry. A strong variation (around 1400%) of the second-harmonic signal as a function of the applied magnetic field is observed. Nonlinear effects and the asymmetric behavior in harmonics can be associated with the anisotropies induced during the fabrication process. These results can lead to improvement of the performance of future magnetoimpedance sensors. © 2003 American Institute of Physics. [DOI: 10.1063/1.1590435]

Amorphous wires with vanishing magnetostriction have been extensively studied in recent years, owing mainly to their potential application in ultrasmall magnetic sensors. These materials show a large variation of impedance upon application of a longitudinal external magnetic field ($H$). This variation, which may reach relative ratios of about 600% in properly treated glass-covered amorphous microwires, is called giant magnetoimpedance (GMI). Since its discovery in amorphous ribbons and wires, there have been many studies whose aim was to increase the GMI effect, mainly through improvement of the soft magnetic properties and favorable induced anisotropies, by means of annealing under an external magnetic field or applied tensile stress. More recently, an asymmetric giant magnetoimpedance (AGMI) effect has been extensively studied. The asymmetrical GMI profile can be obtained through different methods, including the application of a dc bias current. The AGMI has opened new possibilities in sensor conception and linearization.

In this letter, the voltage response of an amorphous fiber is studied in terms of its Fourier components and measured as a function of the applied field $H$, frequency $f$, and amplitude $i_{ac}$ of the driving current. For soft ferromagnetic materials, the permeability strongly depends upon the external magnetic field and current frequency. In these materials, the assumption of a linear magnetization process ($m_{\phi}=\mu_{0}/f_{0}$) is not valid; therefore nonlinear effects can be observed mainly at low dc magnetic field values or at high ac driving current amplitudes. Although we are aware that in such cases the term “impedance” must be used with care, we use the expression “nonlinear magnetoimpedance” (NLMI) to describe the field dependence of the higher harmonics of the impedance signal. Similar nonlinear effects in magnetoimpedance materials have recently been reported. For example, Kurlyandskaya et al. reported nonlinear effects in amorphous FeCoNi magnetic tubes electroploated onto CuBe nonmagnetic wire, which show a NLMI ratio of around 600%.

Antonov et al. investigated the voltage induced in a pick-up coil at 500 kHz, by microwires subjected to axial fields, and also observed nonlinearity. The authors interpreted the data using the quasistatic Stoner–Wohlfarth model, predicting a large second-harmonic component. Gómez-Polo et al. have used Fourier analysis of the time derivative of the circular magnetization to model some aspects of the nonlinear GMI effect.

An amorphous fiber (diameter 40 µm) with nominal composition $\text{Co}_{80.89}\text{Fe}_{4.38}\text{Si}_{8.69}\text{B}_{1.52}\text{Nb}_{4.52}$ was obtained by the melt extraction technique. This material was particularly suited to our purposes, because the production method induces a very interesting distribution of anisotropies within the wire, giving rise to a strong nonlinear response. A 7.0-cm-long as-quenched sample was measured at room temperature. In the GMI experiment, an ac current was applied to the sample, and monitored using an ac current sensor. Measurements of the harmonic components of the induced voltage were obtained using a dual-phase lock-in amplifier, whose time dependence was digitized using a digital oscilloscope whose fast Fourier transform (FFT) was evaluated from the time signal. Longitudinal (parallel to the axis of the fiber) dc magnetic fields were generated by a long solenoid (8.93 kAm$^{-1}$/A). The measurements were made in the frequency range from 100 to 400 kHz, with current amplitudes from 1 to 38 mA.

Figure 1 shows the time dependent signal obtained directly from the oscilloscope for $H=0$ for three different values of the driving current ($i_{ac}=1, 5,$ and 38 mA, respectively). Figure 1(a) shows the voltage wave form, while Fig. 1(b) shows its FFT. In Fig. 1(b), the peaks are wider than the real signal because the FFT was made in a time window of five times the signal period; a wider time window would have resulted in narrower peaks. It may be seen in the figure that for low current values, the voltage wave form follows the sinusoidal excitation, but for higher current values, a significant distortion is observed, in a region indicated by a circle in Fig. 1(a). The voltage measured across the sample is related to the magnetization through the circumferential permeability. For low $h_{\phi}$, the circumferential magnetization...
does not saturate, and the domain magnetization roughly follows the variation of $h_f$. This situation occurs for rather low current values $\sim 1 \text{ mA}$, where the circumferential magnetic field is not strong enough to reach the saturating region of the magnetization curve, and only reversible magnetization processes take place. As the current amplitude is increased, the circular magnetization approaches saturation, and irreversible processes also contribute to the magnetization. Nonlinear effects begin to occur when the magnetic field generated by the ac current reach the nonlinear region of the circumferential hysteresis loops. For higher current values $\sim 5$ and $38 \text{ mA}$, this condition is fulfilled. When an external magnetic field is applied, the relative contribution of harmonic amplitudes change, and, for high enough fields (larger than the circular anisotropy field), the higher harmonics completely disappear. This behavior may be explained using quasistatic models of GMI. In the presence of a circumferential easy axis, the application of a dc longitudinal field continuously reduces the domain wall motion contribution to the magnetization process, and magnetization rotations dominate the magnetization process above the anisotropy field $H_k$.

Figure 2 shows the NLMI as a function of $H$ obtained with respect to its value in a saturating field: $\text{NLMI}_{nf}(\%) = 100 \times \left[ \frac{V_{nf}(H) - V_{nf}(H_{sat})}{V_{nf}(H_{sat})} \right]$, where $V_{nf}$ is the voltage measured in the lock-in amplifier of the harmonic signal of the $n$th order. The figure shows that the NLMI closely follows the conventional GMI profile, with a clear double-peak structure. Figure 2(a) shows the second-harmonic (2$f_0=600 \text{ kHz}$) NLMI ratio as a function of the axial dc field $H$. The inset shows the fundamental impedance response (corresponding to conventional GMI). (b) Third-harmonic (3$f_0=900 \text{ kHz}$) NLMI ratio as a function of $H$. In the inset the highly asymmetrical behavior is clear for increasing axial field. In both graphs, $i_{ac}=3 \text{ mA}$. 

FIG. 1. (a) Time voltage response for three values of current with $H=0$. The circles indicate distortions for high values of current. (b) The FFT of the time-dependent voltage, showing the higher harmonics generated for increasing values of current.

FIG. 2. (a) The second-harmonic (2$f_0=600 \text{ kHz}$) NLMI ratio (defined in the text) as a function of the axial dc field $H$. The inset shows the fundamental impedance response (corresponding to conventional GMI). (b) Third-harmonic (3$f_0=900 \text{ kHz}$) NLMI ratio as a function of $H$. In the inset the highly asymmetrical behavior is clear for increasing axial field. In both graphs, $i_{ac}=3 \text{ mA}$. 


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whose maxima are located in the vicinity of the circular anisotropy field. It is worth emphasizing that the second-harmonic component presents an extremely large variation in the output voltage (around 1400%), for rather small applied fields (less than 1 kA m\(^{-1}\)). This value is about 20 times higher than the variation of the conventional GMI. In addition, the asymmetric trend of GMI is not only present, but is enhanced for higher harmonics.

For prospective sensor applications, it is important to characterize the current and frequency dependence of the NLMI. In Fig. 3, the second-harmonic component amplitude at the field where the peak occurs is plotted as a function of the ac driving current frequency. The second harmonic shows a behavior similar to that of the fundamental, with an increase of NLMI with frequency. The NLMI is very sensitive to the amplitude of the ac driving current, and the frequency dependence is also a function of its value. It was also observed that the asymmetric profile in the field dependence of the NLMI is enhanced as frequency increases, for currents of 2 and 3 mA, while for 1 mA the opposite behavior occurs with a decrease of the asymmetry with increasing frequency.

The higher harmonic intensities present enhanced asymmetry when compared to the fundamental GMI signal. The gradual appearance of distortion in the voltage signal, and the consequent appearance of higher harmonic components, can be directly associated with the circular magnetization process. In Fig. 4, the maximum second harmonic voltage signal is shown as a function of the ac field generated by the ac current in the fiber surface \( h_{a}(a) = i_{ac}/2\pi a \). The measurement was repeated for selected values of frequencies. The field where \( V_{2f} \) reaches its maximum also depends on the current frequency, and for frequencies above 200 kHz the maximum occurs at the same values of current. We are presently studying the NLMI in wires under controlled torsion and tension, in order to clarify the effect of systematically varied induced anisotropy.

In conclusion, fundamental, second- and third-harmonic components of the voltage signal in a GMI experiment have been measured in as-quenched amorphous Co\(_{0.80}\)Fe\(_{0.38}\)Si\(_{0.68}\)B\(_{1.52}\)N\(_{0.52}\) fibers. A large signal variation was found in the second harmonic component (1400%), at relatively low applied magnetic fields. Like the fundamental signal, the higher harmonics show an asymmetry in their intensity. While quasi-static models\(^{5,11,16,17}\) give a good indication of the circumstances in which higher harmonics will be important, they are not likely to accurately predict amplitudes, and they can obviously not be used to explain the frequency dependence shown in Figs. 3 and 4. This presents a serious theoretical challenge, and will not necessarily be a simple task. Despite this, these results can be relevant in the design of new microsensitive probes using GMI. The large NLMI ratios obtained in this work can help to increase the sensitivity, while the asymmetry can be used to improve the linearization of a GMI-based sensor. Nonlinear magnetoeimpedance sensors can be designed to be somewhat analogous to conventional flugate sensors, with high sensitivity of the second-harmonic response of the magnetization to external magnetic field. In the case presented in this letter, the high sensitivity of the second-harmonic signal to applied field will probably permit the design of novel field sensors, with improved miniaturization, linearization, and sensitivity.

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