Modulation of electromagnetic waves by alternating currents through left-handed ferromagnetic microwires

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We present experimental results of electromagnetic wave modulation by the application of AC currents along a ferromagnetic microwire at the frequency range where left-handed transmission is observed. It is demonstrated that transmitted microwave signals through a waveguide mount are modulated by the current applied to the wire. From the measurements, we have extracted information about the magnetic susceptibility behavior of the microwires. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3694006]

I. INTRODUCTION

In the last few years, artificial magnetism has fueled a huge research effort in connection with the study of micro-structured artificial media, also termed metamaterials. These structures are interesting since they provide unique features such as those used in negative refraction devices,[1] super-resolution lenses,[2] or cloaking shells.[3] In this context, attention has been recently paid to the use of magnetic materials taking advantage of their magnetic activity to design double negative media.[4–9] In these works, solutions were based on the use of different types of magnetic materials to obtain a double negative response with adjustable characteristics. Moreover, experimental and numerical evidence of left-handed or backward wave propagation in these microstructures was studied. It was also demonstrated that the use of ferromagnetic materials as constituents of micro-structured devices has the important asset of providing tunability of the electromagnetic (EM) responses as a function of an adjustable applied magnetic field.[6–8] It is known that the ferromagnetic resonance (FMR) phenomenon typically occurs at microwave frequencies for different types of metallic alloys. Historically, FMR phenomena were studied in terms of material characterization, extraction of resonant permeability models or experimental investigation of resonant configurations.[10–12] The same analysis techniques have been used specifically in the characterization of amorphous magnetic microwires.[12–14] Particularly, a phenomenological theory of FMR in thin ferromagnetic wires has been reported by Kraus *et al*.[14,15]

In this paper, we demonstrate the modulation of the EM response of a ferromagnetic microwire in a waveguide mount by using an AC current flowing along it. Therefore, on top of the already studied tunable response of this type of element via an applied magnetic field[6,7] and an applied DC current,[8,16] we now investigate the possible application of this type of technology as a microwave modulating system.

II. EXPERIMENTAL SETUP

The employed glass coated amorphous microwire has a general composition given by $(Co_{100-x}Fe_x)_{0.725}Si_{12.5}B_{15}$. Parameter x represents here the variable fraction of iron in the alloy. In practice, we have used an $x = 6$ sample, particularly because this compound has a close to zero magnetostriction constant. This microwire has a core of ferromagnetic material with approximate radius $r = 2.5$ μm and a glass coat between 2 and 5 μm. Figure 1 shows a schematic of the experimental measurement setup employed. The microwire is inserted in a hollow metallic waveguide; it is centered with respect to the lateral walls and vertically oriented. The top and bottom metallic walls of the waveguide have been drilled, and the microwire pierces it. The waveguide employed is of standard WR-62 type and it is used in the TE_{10} dominant mode frequency range (from 12 to 18 GHz). In any case, the impinging radio-frequency wave has an electric field, e_{rf}, parallel to the wires axis and a magnetic field, h_{rf}, in the perpendicular plane. This part of the setup was carefully analyzed in previous works,[6,7] and this field configuration permits to properly excite the FMR of the microwire. Again, an electromagnet is used to polarize the microwire with a static magnetic field, H_0, which is parallel to the wire axis. The novelty is here that we have used an AC function generator to produce a modulated current excitation flowing through the microwire. The two ends of the microwire are hence connected to an AC voltage source.

Transmission coefficients are measured in terms of S-parameters with a vector network analyzer (VNA). The AC waveform delivered by the function generator has a sinusoidal shape with peak values ranging up to 10 V_{pp}. Combined with this peak AC voltage, a DC offset voltage can be optionally applied to the microwire circuit.

III. THEORETICAL MODEL

In the FMR region the skin depth (δ) is much smaller than the radius (R) of the microwire and it behaves like a plane[15] (Fig. 1). This microwire has a nearly zero magnetostriction constant ($\lambda_s = -10^{-7}$), and its domain structure has an axial magnetization in the central region of the microwire and circular magnetization in the region close to the surface. The current flowing through the microwire originates a helicoidal magnetization. If the anisotropy field, of magnetoelastic origin, is perpendicular to the axial direction in the microwire, then $\phi = \varphi$ in Fig. 1.

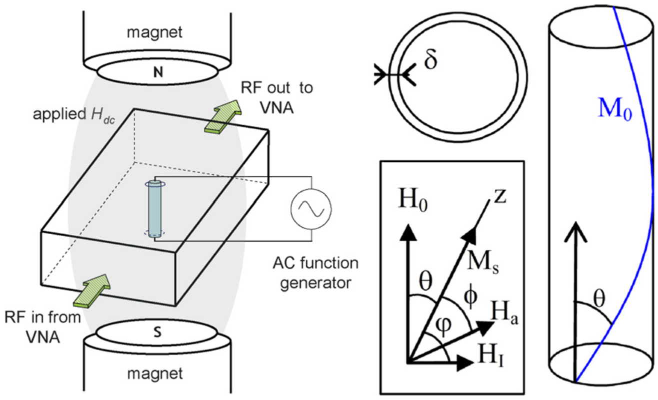

FIG. 1. (Color online) (a) Schematic view of the waveguide setup employed in the experiments for configurations including an AC function generator to modulate the transmitted RF signal in the waveguide, (b) scheme of the helicoidal magnetization on the microwire, and the plane equivalence due to the skin depth (δ), with all parameters and components of magnetic field implied in Eqs. (1)–(4). Note that with the actual experimental conditions, the sample is saturated in the axial direction.

In brief, the dynamic susceptibility of a ferromagnetic material can be obtained from the Landau-Lifschitz-Gilbert equation of motion of the magnetization:

$$\frac{d\vec{M}}{dt} = -\mu_0\gamma(\vec{M}\times\vec{H}) + \frac{\alpha}{M_s}\left(\vec{M}\times\frac{d\vec{M}}{dt}\right), \tag{1}$$

where $\gamma = g\mu_B/\hbar$ is the gyromagnetic ratio, α is a damping parameter, M_s the saturation magnetization and $\vec{M} = \vec{M}_0 + \vec{m}_{rf}$ is the total magnetization (static and dynamic, respectively). The total magnetic field is $\vec{H} = \vec{H}_0 + \vec{H}_a + \vec{H}_I + \vec{h}_{rf}$, where the different components are

$$\vec{H}_a = \frac{H_K}{M_S}\vec{n}(\vec{n}\cdot\vec{M}), \quad H_K = \frac{2K}{\mu_0 M_S}, \quad K = \frac{3}{2}\lambda_S\sigma, \quad H_I = \frac{Ir}{2\pi R^2}, \tag{2}$$

where H_a is the anisotropy field, K is the anisotropy constant and σ the stress,[10] H_I is the circular magnetic field produced by current I, H_0 is the external bias magnetic field, and h_{rf} the microwave magnetic field. From Eq. (1), the dynamic susceptibility is determined from Ref. 17 where we have added the term corresponding to H_I:

$$\chi_{xx}(\omega) = \frac{-\omega_M[\omega_{OKI} + j\omega_\alpha]}{\omega^2 - (\omega_{OKI} + j\omega_\alpha)(\omega_{OI} + \omega_M + j\omega_\alpha)}$$

$$\omega_{OKI} = \mu_0\gamma[H_0\cos\theta + H_K\cos 2\phi + H_I\cos 2\varphi]$$

$$\omega_{OI} = \mu_0\gamma[H_0\cos\theta + H_K\cos^2\phi + H_I\cos^2\varphi]$$

$$\omega_M = \mu_0\gamma M_0 \quad \omega_\alpha = \frac{\omega\alpha}{\mu_0\gamma}. \tag{3}$$

We have to clarify that with our actual experimental conditions, the sample is magnetically saturated in the axial direction, and the model used in Eq. (3) is employed to calculate an effective axial magnetic field.

The frequency of ferromagnetic resonance (FMR) is

$$\omega_{FMR} = \sqrt{\omega_{OKI}(\omega_{OI} + \omega_M)}. \tag{4}$$

We have taken into account the dynamic demagnetization factors, $N_x = 1$ and $N_y = N_z = 0$ for a plane.[13–15] This is justified since the value of the skin depth is given by $\delta = \delta_0/\sqrt{\mu_r}$, with $\delta_0(10\text{ GHz}) = 5\ \mu$m. Assuming that μ_r, in the region of interest, takes values higher than 10, then δ is around 1.5 μm, hence lower than the wire radius.

The azimuthal field depends on the skin depth, the anisotropy distribution generated during the fabrication process and the applied current along the wire [see Eq. (2)]. This field is not constant with the radius and its variation will generate a widening of the resonance line.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 2 plots the transmission coefficient S_{21} with static DC magnetic field has a parameter. These results reproduce the ones already reported for other samples with different chemical composition.[6] For this sample we have considered $\gamma \approx 1.76\cdot 10^{11} T^{-1}s^{-1}$, $\mu_0 M_s \approx 0.6\ T$, and $\alpha \approx 0.02$. Thus, for $H_0 = 250$ kA/m the following frequency is obtained from Eq. (4); $f_{FMR} \approx 15$ GHz ($I = 0$, $H_K = 0$, $\theta = 0$).

Figure 3 shows the transmission coefficient S_{21} for $H_0 = 250$ kA/m as a function of the DC current. A nonlinear relation between peak transmission frequency and applied current is observed.

A further characterization of the sample has been done by vibration sample magnetometer (VSM),[18] and a longitudinal hysteresis loop is reported in Fig. 4. Thus, it can be concluded that the sample has a domain structure consisting of an inner core with axial magnetization, and a shell with circular magnetization, as schematically described in the inset.

A wave function generator is employed to produce a sinusoidal current along the wire. We then capture the modulated transmission coefficient through the complete waveguide mount by using a time domain measurement feature of the VNA. We have used the VNA in demodulator mode centered at 17 GHz to demodulate the S_{21} signal. Data are displayed in Fig. 5, where the transmission coefficient is

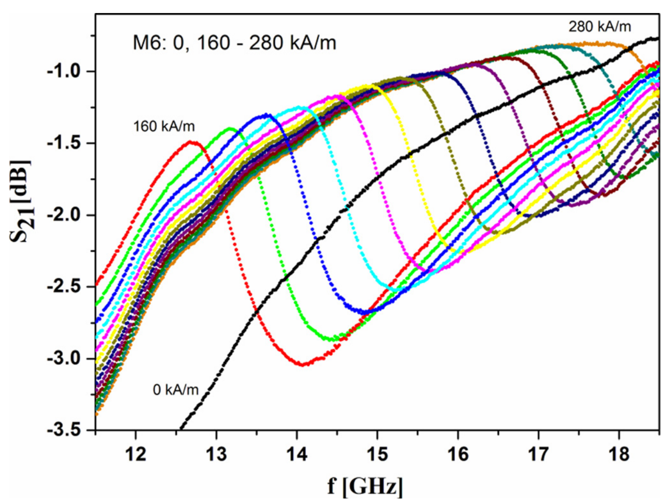

FIG. 2. (Color online) Transmission peak as a function of static magnetic field as a parameter, with range 160 to 280 kA/m in steps of 10 kA/m.

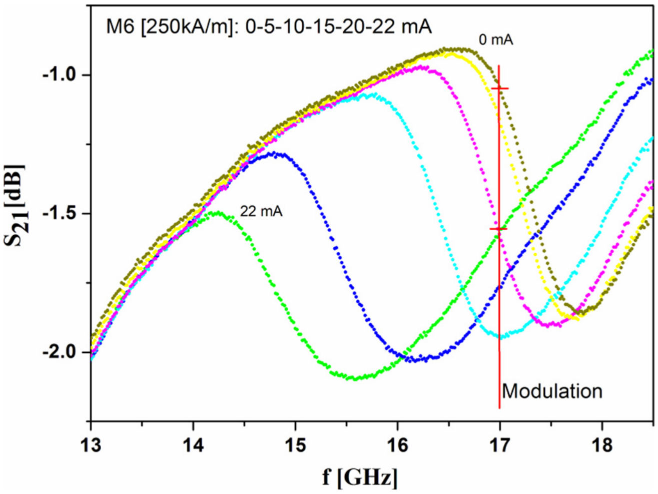

FIG. 3. (Color online) Transmission coefficient as a function of DC current flowing through the microwire for a static magnetic field of 250 kA/m. Vertical line defines the frequency at which modulation is here performed (17 GHz).

represented as a function of time for different modulated current signals. The applied current wave has a sinusoidal shape and has a frequency of 1 Hz. Signal is captured at 17 GHz, with $H_0 = 250$ kA/m. The estimated microwire resistance is 650 Ω which is obtained from a voltage over current ratio in the circuit. So, the ratio between voltage and current corresponds to 1.5 mA/V.

Curve 1 in Fig. 5(a) displays the transmitted signal for an alternating voltage applied to the microwire of amplitude $V_{pp} = 10$ V (with a corresponding current of 15 mA_{pp}) and with no DC offset. Curve 2 corresponds to the transmitted signal for an alternating voltage applied to the microwire of amplitude $V_{pp} = 2$ V (3 mA_{pp}) and with offset of $V_{\mathrm{DCoffset}} = 4$ V (6 mA).

Curve 1 in Fig. 5(b) depicts the transmitted signal for an AC voltage applied to the microwire of amplitude $V_{pp} = 5$ V (corresponding current 7.5 mA_{pp}) and with DC offset of $V_{DCoffset} = 2$ V (3 mA). Finally, curve 2 plots the transmitted signal for an amplitude modulated alternating voltage along the wire, with a 10 Hz carrier frequency, and 1 Hz modulating

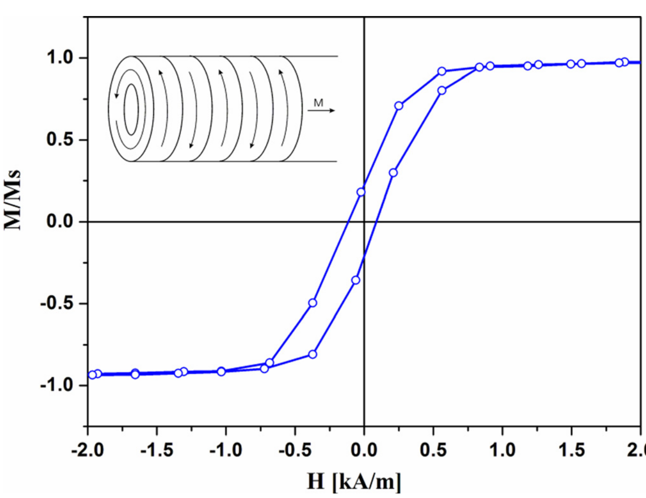

FIG. 4. (Color online) Measured longitudinal hysteresis loop.

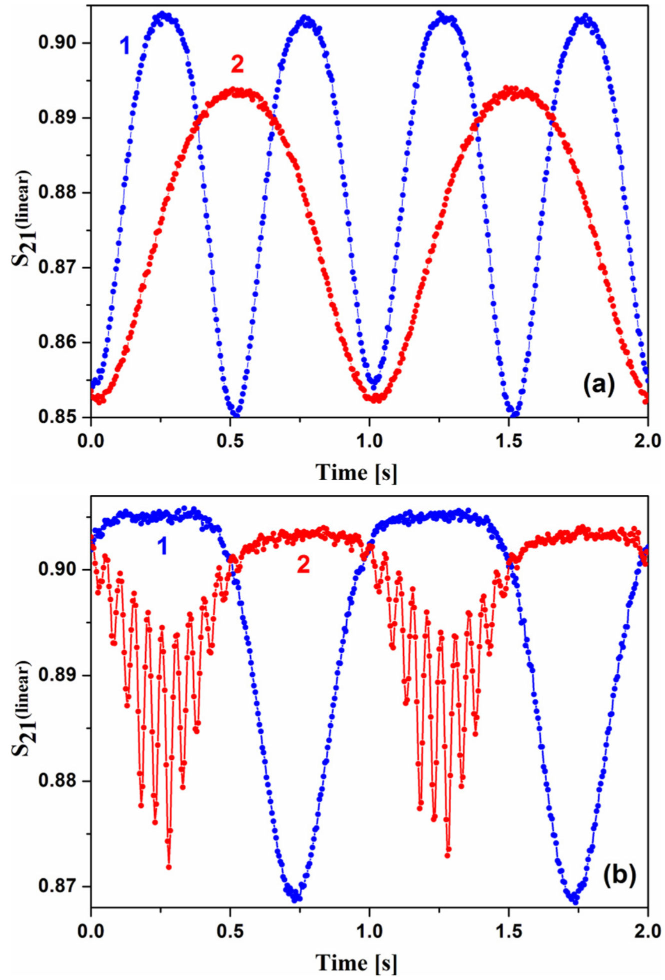

FIG. 5. (Color online) Transmitted RF waveforms as a function of time for a 1 Hz function generator. Settings are in (a), curve 1: 10 V_{pp} no DC offset; curve 2: 2 $V_{pp} + 4$ V_{DCoffset}. In (b) curve 1: 5 $V_{pp} + 2$ V_{DCoffset}; curve 2: 10 V_{pp} AM modulation with a 10 Hz carrier and a 1 Hz modulating signal (100% modulation index).

frequency with 100% modulation index, and amplitude $V_{pp} = 10$ V (15 mA_{pp}).

From the measured waveforms, we can note some remarks. For curve 1 of Fig. 5(a), we get double frequency response with respect to the input one. For curve 2, the application of a DC offset to the modulated signal generates a signal with the same frequency of the excitation one. In Fig. 5(b), the amplitude of the transmitted signal is saturated above a maximum threshold for both curves.

Let us recall that the total absorption coefficient (including electric and magnetic losses) is approximately $C_{\mathrm{abs}} \approx 1 - |S_{21}|^2$ in this type of structures, since the magnitude of the reflection coefficient $|S_{11}|^2$ is lower than 0.1 in all the frequency range.[6–8]

Data in Fig. 5(b) indicate that below a 3 mA (2V) amplitude there is no variation of the susceptibility and over 3 mA there is a non linear variation. As a consequence, in the range from -3 to $+3$ mA there is no variation in the absorbed power, and the level at the peak frequency of S_{21} remains constant (see Fig. 3). Therefore, it can be concluded that this effect is due to the nonlinear response of the magnetization of the ferromagnetic microwire.

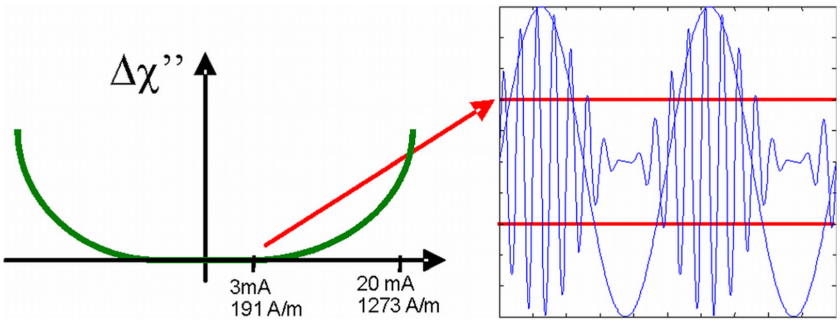

FIG. 6. (Color online) Variation of transversal susceptibility as a function of the DC current applied to the microwire. AM signal applied to the microwire that produces the signal plotted in curve 2 Fig. 5(b).

Figure 6 shows a schematic drawing of the variation of the imaginary susceptibility, according to the previous discussion. The horizontal lines on the AM modulated signal shown in Fig. 6 (right panel) define the threshold current of non-linear response; below 3 mA the signal is rapidly and strongly attenuated.

V. CONCLUSION

In summary, we have analyzed the use of an AC current circuit biasing a ferromagnetic microwire which is inserted in an RF waveguide mount. Our results and conclusions support this proposal as a tunable mechanism to extend the operation bandwidth and functionality beyond that of previous studies. In this sense, we have proposed and studied the use of an AC current circulating through the wire as a means of modulating the transmitted RF waveform at the enhanced transmission frequency. This scheme permits also the assessment of some of the magnetic and electric characteristics of the ferromagnetic microwire.

ACKNOWLEDGMENTS

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[1]N. Engheta and R. W. Ziolkowski, eds., *Metamaterials. Physics and Engineering Explorations* (Wiley InterScience, IEEE Press, Piscataway, NJ, 2006).
[2]J. B. Pendry, Phys. Rev. Lett. **85**, 3966 (2000).
[3]D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, Science **314**, 977 (2006).
[4]H. Zhao, J. Zhou, L. Kang, and Q. Zhao, Opt. Express **17**, 13373 (2009).
[5]H. Zhao, L. Kang, J. Zhou, Q. Zhao, L. Li, L. Peng, and Y. Bai, Appl. Phys. Lett. **93**, 201106 (2008).
[6]H. Garcia-Miquel, J. Carbonell, V. E. Boria, and J. Sanchez-Dehesa, Appl. Phys. Lett. **94**, 054103 (2009).
[7]J. Carbonell, H. Garcia-Miquel, and J. Sánchez-Dehesa, Phys. Rev. B **81**, 024401 (2010).
[8]H. Garcia-Miquel, J. Carbonell, and J. Sanchez-Dehesa, Appl. Phys. Lett. **97**, 094102 (2010).
[9]I. Liberal, I. Ederra, C. Gómez-Polo, A. Labrador, J. I. Pérez-Landazabal, and R. Gonzalo, IEEE Trans. Microwave Theory Tech. **59**, 517 (2011).
[10]C. Kittel, Phys. Rev. **73**, 155 (1948).
[11]S. E. Lofland, S. M. Baghat, A. L. Ju, G. C. Xiong, T. Venkatesan, R. L. Greene, and S. Tyagi, J. Appl. Phys. **79**, 5166 (1996).
[12]S. E. Lofland, H. García-Miquel, M. Vázquez, and S. M. Baghat, J. Appl. Phys. **92**, 2058 (2002).
[13]H. García-Miquel, M. J. Esbrí, J. M. Andrés, J. M. Garcia, J. M. Garcia-Beneytez, and M. Vázquez, IEEE Trans. Magn. **37**, 561 (2001).
[14]L. Kraus, G. Infante, Z. Frait, and M. Vázquez, Phys. Rev. B **83**, 174438 (2011).
[15]L. Kraus, Czech. J. Phys. **32**, 1262 (1982).
[16]M. Ipatov, A. Chizhik, V. Zhukova, J. Gonzalez, A. Zhukov, J. Appl. Phys. **109**, 113924 (2011).
[17]L. Kraus, J. Magn. Magn. Mater. **195**, 764 (1999).
[18]H. García-Miquel, J. M. Garcia, J. M. Garcia-Beneytez, and M. Vázquez, J. Magn. Magn. Mater. **231**, 38 (2001).