Left handed material based on amorphous ferromagnetic microwires tunable by dc current

H. García-Miquel, J. Carbonell,[a] and J. Sánchez-Dehesa
Grupo de Fenómenos Ondulatorios, Departamento de Ingeniería Electrónica, Universidad Politécnica de Valencia, Camino de Vera, s/n, E-46022 Valencia, Spain

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Tuning of the transmission characteristics of amorphous ferromagnetic microwires through a dc current is demonstrated. These structures are studied in the frequency region where they present double negative behavior. It is found that their frequency response shifts with small dc currents circulating along the wires. It is observed that the dc current tends to compensate and even cancels the resonant peak associated to the static magnetic field applied along the wire axis. The phenomenon behind these findings is discussed in terms of the torque exerted by the field created by the current on the plane perpendicular to the wire axis. © *2010 American Institute of Physics*. [doi:10.1063/1.3485055]

During the past years, a great research activity has been focused on the control of the electromagnetic (EM) wave dispersion in different types of artificial microstructures, usually termed metamaterials. The possibility of controlling wave propagation in media typically made from subwavelength inclusions has opened a huge amount of potential applications like negative refraction devices,[1] super-resolution lenses,[2] or cloaking shells.[3] At the same time it has raised a number of important challenges, notably those going beyond the confirmation of these physical phenomena and toward practical application devices. Since metamaterials are dispersive in essence, one of their most recognized drawbacks is their limited operation frequency range. 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.[4–6] In these works, solutions were based on the use of magnetic material arrays to obtain a double negative response with, in particular, adjustable responses. 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 microstructured devices has the important asset of providing tunability of the EM responses as a function of an adjustable applied magnetic field. It is known that the ferromagnetic resonance (FMR) phenomenon typically occurs at microwave frequencies for different types materials. Historically, FMR phenomena were studied in terms of material characterization,[7–9] extraction of resonant permeability models or experimental investigation of resonant configurations.[10,11] But the same techniques have also been used specifically in the characterization of amorphous magnetic microwires.[12–14]

In this paper, we demonstrate the tuning of the EM response of ferromagnetic microwires by using a dc current flowing through them. Therefore, on top of the already studied tunable response of these elements via an applied magnetic field, an applied dc current is now used as an additional means of shifting the resonant response to an EM wave impinging on the wires. This permits one to increase the design capabilities and operation frequencies with the active use of an adjusting parameter not studied previously.

The employed glass coated amorphous microwires have a general composition $(\mathrm{Co}_{100-x}\mathrm{Fe}_x)_{0.725}\mathrm{Si}_{12.5}\mathrm{B}_{15}$. Parameter x represents here the variable fraction of iron in the alloy. In practice, we use samples with $x=2$ and 70 to cover different material compositions. The employed microwires have a ferromagnetic material core of radii ranging from $r=2$ to 3 μm and a glass coat between 2 and 5 μm, due to the dispersion inherent to the fabrication method. Figure 1(a) shows a scanning electron microscope view of a sample microwire (glass coat partially removed). Different configurations of the experimental setup, which is schematized in Fig. 1(b), are employed according to the foreseen operation frequency range. Microwires are inserted in a hollow metallic waveguide; they are centered with respect to the lateral walls and vertically oriented. Waveguides of different sizes are employed, since they are used in their respective TE_{10} dominant mode frequency range (WR-90 from 8 to 12 GHz and WR-62 from 12

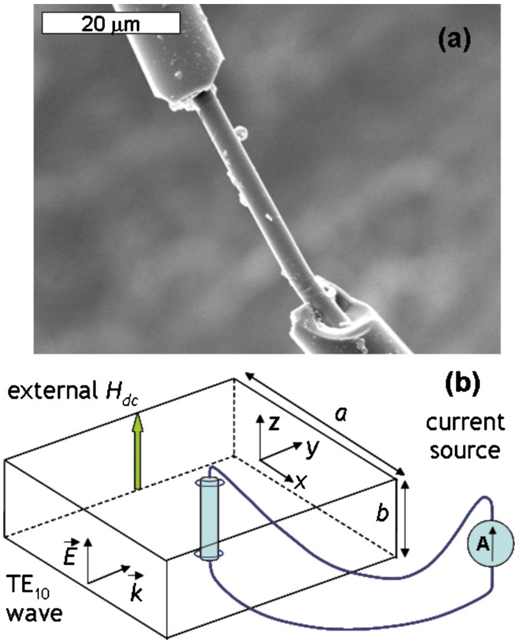

FIG. 1. (Color online) (a) SEM view of a partially removed glass coat amorphous microwire, (b) Schematic view of the waveguide setup employed in the experiments for configurations including a dc current source.

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[a] Electronic mail: jorcarol@upvnet.upv.es.

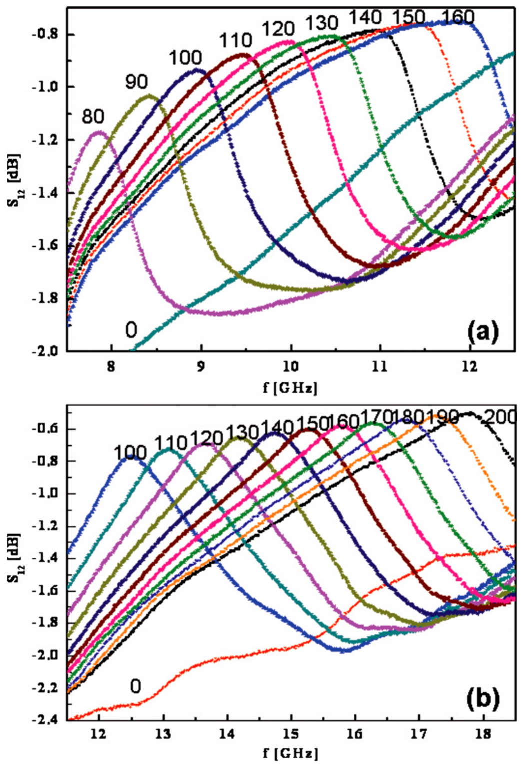

FIG. 2. (Color online) Measured transmission coefficient for $x=2$ (a) and $x=70$ (b) microwires vs frequency for a varying applied magnetic field H_0 (tag on each curve, units in kA/m).

to 18 GHz). In all cases, 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.[6,15] Again, an electromagnet is used to polarize the microwires with a static magnetic field, H_0, which is parallel to the wire axis. The originality is here that we have used a dc current excitation flowing through the microwire. For this purpose, the top and bottom metallic walls of the waveguide have been drilled, and the microwire pierces it. The two ends of the microwire are hence connected to a dc current source.

Transmission coefficients are measured in terms of S-parameters with a network analyzer. The variation in the static magnetic field intensity is measured with a gauss meter. The dc current delivered by the source has values ranging from 0 to 20 mA.

Figures 2(a) and 2(b) show the measured transmission coefficient for single wire elements (with $x=2$ and $x=70$, respectively), and a varying applied external static field H_0. In these results, there is no current applied from the source and, therefore, the transmission enhancement observable when H_0 is applied corresponds to the generation of a double negative response of the microwire in frequency range between FMR and ferromagnetic antiresonance (FMAR) frequencies. Comparing both cases, data show coherent evolutions between them and also with the results previously published for other alloy compositions.[12,15] It is also shown that, for the case $x=2$, the field H_0 necessary to obtain the transmission band in the range 12 to 18 GHz is around twice of that for the case $x=70$. This is basically due to the different saturation magnetization Ms of the samples, and also to the different magnetic anisotropy.[14] This parameter is dependent on the chemical composition of the wire core; it was empirically found[12] that $\mu_0 M_{s(x=2)}=0.55$ T and $\mu_0 M_{s(x=70)}=1$ T. Therefore this factor of approximately 2 between both values can be recovered from the necessary magnetic field values applied to both wires to obtain a similar resonance frequency.

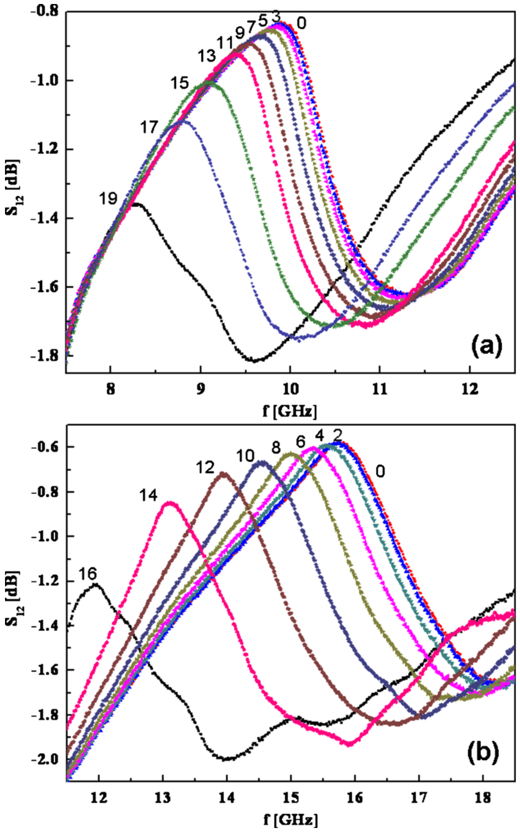

FIG. 3. (Color online) Measured transmission coefficient vs frequency for $x=2$ (a) and $x=70$ (b) microwires, with a fixed applied magnetic field ($H_0=120$ kA/m and 160 kA/m, respectively), and a variable applied direct current (tag on each curve, units in milliampere).

In a second step, a dc with variable magnitude is applied to the wire by the current source. At the same time, H_0 is kept constant at a fixed value in order to polarize the samples and fix the transmission window within the waveguide operation range. In particular and for these experiments, $H_0=120$ kA/m for the $x=2$ sample and $H_0=160$ kA/m for the $x=70$ sample. Figure 3 shows the transmission spectra for both samples as a function of the applied dc current. The main observable effect is the fact that an increasing applied current shifts the transmission window toward lower frequencies. For small dc currents, below 3 mA, the transmission peak is barely affected, but for currents above 3 mA the frequency shift progressively increases. Notice that frequency shifts are very important taking into account the relatively small applied currents necessary to produce them. Ferromagnetic resonance is therefore very sensible to a dc current applied simultaneously with the static magnetic field. Moreover, it is observed that as higher is the dc current as lower is the recorded peak amplitude; i.e., the resonant response is progressively degraded with increasing dc currents, even to the point of quenching it if the current is large enough. Incidentally, let us remark that the double negative response of the microwires is associated in part to the conductive properties of the alloy containing metallic elements (Fe and Co). In the experiments, it is therefore proven that ferromagnetic resonance does not cancel conductivity, since a direct current can flow through the wires even within the resonance conditions. Approximately, the transmission band disappears for threshold currents of 17 mA and 20 mA for the $x=70$ (with $H_0=160\ \text{kA/m}$) and $x=2$ (with $H_0=120\ \text{kA/m}$) samples, respectively.

From the experimental results, we conclude that the current flowing through the wire causes an effective modification of its magnetic properties as follows. First, it is important to stress that the frequency range where the wires present a double negative behavior (i.e., negative ε and negative μ), which is the region where data are obtained, is in between ω_{FMR} and ω_{FMAR}. These frequencies are deduced by solving the Landau–Lifshiftz equation of motion for the magnetization. Thus, in absence of a dc current, the frequencies are as follows:[6,7]

$$\omega_{\text{FMR}} = \mu_0 \gamma \sqrt{H_{\text{eff}}(H_{\text{eff}} + M_s)}, \tag{1}$$

$$\omega_{\text{FMAR}} = \mu_0 \gamma \sqrt{H_{\text{eff}}(H_{\text{eff}} + 2M_s)}, \tag{2}$$

where

$$H_{\text{eff}} = H_0 + H_K, \tag{3}$$

H_0 being the external static magnetic field applied by the electromagnet and H_K is the anisotropy field of the sample due to magnetoelastic anisotropy.[7,13] This field H_K, as proposed by Kittel, takes into account the anisotropy energy due to the chemical and mechanical characteristics of the microwire. Moreover, let us remark that H_K is negative in samples with negative magnetostriction constant (for $x=2$, $H_K=-1\ \text{kA/m}$) and positive for sample with positive magnetostriction constant (for $x=70$, $H_K=27\ \text{kA/m}$).[12]

Now, when a dc current is applied an additional effective field H_I appears along the same direction than H_0 and H_K. This effective field H_I is physically understood in terms of the torque exerted on the axial magnetization by the field induced by the dc current on the plane perpendicular to the wire axis. Therefore, H_{eff} becomes

$$H_{\text{eff}} = (H_0 + H_K - H_I). \tag{4}$$

Let us note that H_I and H_K have a different origin; i.e., H_K is a material dependent intrinsic field and H_I is directly associated to the applied dc current. In our model, they both impact on the total effective field applied to the microwire.

Based on the previous discussion, Fig. 4(a) shows the maximum transmission frequency versus applied dc current, while Fig. 4(b) summarizes the retrieved field H_I as a function of the current magnitude. It is worth mentioning that the obtained results are independent of the current sign, as it happens with the sign of the polarization field H_0. Also, the magnitude at the peak transmission as a function of the current is displayed. It shows a rapid degradation, consequence of the cancellation between external applied field H_0 and internally induced fields H_K and H_I.

In summary, an experimental and model analysis of tunable ferromagnetic microwires in a waveguide has been reported. Particularly, we have demonstrated that small dc currents circulating through the wires can be used as a tuning parameter. The dc current allows shifting the frequency at which the enhancement of the transmission response is found under external magnetic fields. Experimental results demonstrate that this tuning parameter generates an effective field along the wire axis that partially cancels and even quenches the externally applied static magnetic field. The tuning features of the studied structures are of great relevance in the metamaterial context, owing to the possibility of extending the operational bandwidths.

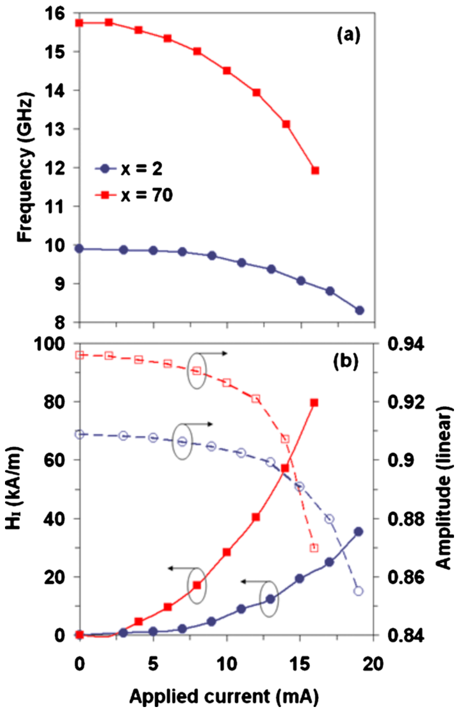

FIG. 4. (Color online) (a) Maximum transmission frequency vs dc current; (b) Effective field (bold symbols) derived from the applied dc current flowing through the ferromagnetic microwire for both samples and polarization fields, and variation in the maximum transmission amplitude (empty symbols). The lines between symbols are guides for the eye.

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