Modelling of metamaterials based on ferromagnetic wires

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Abstract

Ferromagnetic microwires are investigated as fundamental components to generate metamaterials with double negative parameters. Electric and magnetic responses are, respectively, based on the finite conductivity and ferromagnetic resonance of the wires that in turn depend on their chemical composition. Tuning properties of samples are investigated in terms of an applied magnetic field. The samples are measured and simulated in a waveguide environment for a large microwave frequency range. Numerical modelling supports the experimental results and helps to understand the physics involved in the transmission phenomena. Radius and conductivity of the wires are pointed out as the most critical parameters to generate a double negative response.

1. Introduction

Research on metamaterials has been basically driven by the development of microstructures relying on the artificial magnetism generated by split ring resonators (SRRs) or other types of current loops. Nevertheless, this approach often requires the combination of two separate arrays being able to combine, in a given frequency range, a double (electric and magnetic) negative response. More recently, attention has been paid to the use of magnetic materials taking advantage of their magnetic activity to design double negative media. In this case, solutions were also based on the combined use of ferrites and metallic wire arrays. In this context, it has been recently confirmed that an array of conducting ferromagnetic microwires can provide a double negative response, with experimental evidence of left-handed or backward wave propagation in the microstructure, [1].

2. Numerical modelling of ferromagnetic microwires

The modelling of the material properties of the microwires has been realized simultaneously considering both characteristics in terms of electric and magnetic responses, [2]. The electrical response of the wires is related to the finite conductivity of the alloy composition. A fixed value of $\sigma = 6.7\ 10^5$ S/m is assigned to the wire region. At microwave frequencies, where the ferromagnetic resonance effects occur, the authors assume that conductivity is a good and stable magnitude to model the electric response of the wires. The conductivity of the amorphous ferromagnetic alloy is smaller than the one of a crystalline alloy. Its moderate value will increase the skin depth and hence the penetration of electromagnetic fields inside the wires.

The magnetic response is much more complex and is essentially driven by the FMR phenomenon associated to the wires. As qualitatively proposed in [1], the magnetic response of the microwires can be modelled with a Lorentz-type behaviour defined by the characteristic parameters of the wires (including in particular losses) and the external applied field H_0. Since the excitation wave is the TE_{10} mode of the waveguide, the high frequency magnetic field, h_{rf}, will have both components in the $\vec{x}$ and $\vec{y}$ directions; see Fig. 1. The relative magnetic permeability μ, and the dynamic susceptibility χ, of the bulk material employed in the simulation can be described with the following tensor model:

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$$\mu = 1+\chi = \begin{pmatrix}\mu_{xx} & \mu_{xy}\\ \mu_{yx} & \mu_{yy}\end{pmatrix} = \begin{pmatrix}1+\left(X_p - iX_s\right) & i\left(K_p - iK_s\right)\\ -i\left(K_p - iK_s\right) & 1+\left(X_p - iX_s\right)\end{pmatrix}, \qquad (1)$$

where the susceptibility elements are found to be:

$$X_p = \frac{\omega_0\omega_m(\omega_0{}^2 - \omega^2) + \omega_0\omega_m\omega^2\alpha^2}{\left[\omega_0{}^2 - \omega^2(1+\alpha^2)\right]^2 + 4\omega_0{}^2\omega^2\alpha^2},\quad X_s = \frac{\omega\omega_m\alpha(\omega_0{}^2 + \omega^2(1+\alpha^2))}{\left[\omega_0{}^2 - \omega^2(1+\alpha^2)\right]^2 + 4\omega_0{}^2\omega^2\alpha^2}, \quad (2)$$

$$K_p = \frac{\omega\omega_m(\omega_0{}^2 - \omega^2(1+\alpha^2))}{\left[\omega_0{}^2 - \omega^2(1+\alpha^2)\right]^2 + 4\omega_0{}^2\omega^2\alpha^2},\quad K_s = \frac{2\omega^2\omega_0\omega_m\alpha}{\left[\omega_0{}^2 - \omega^2(1+\alpha^2)\right]^2 + 4\omega_0{}^2\omega^2\alpha^2}, \quad (3)$$

and $\omega_m = \mu_0\gamma M_s$ is the resonance frequency at the saturation limit, $\gamma = 1.93\ 10^{11}\ \mathrm{T}^{-1}$ ($g = 2.2$), is the gyromagnetic ratio, and $\omega_0 = \mu_0\gamma H_0$ is the Larmor resonance frequency. A dimensionless damping factor, taking into account magnetic losses, is set to $\alpha = 0.02$, by fitting the experimental data. It is essential to note that the above model does not consider the actual geometry, since it defines the bulk susceptibility applied to the wire region of the simulation domain. Nevertheless, the simulation results take into account the geometry dependent characteristics of the resonance phenomena by meshing the inside of the wire and calculating the full-wave patterns.

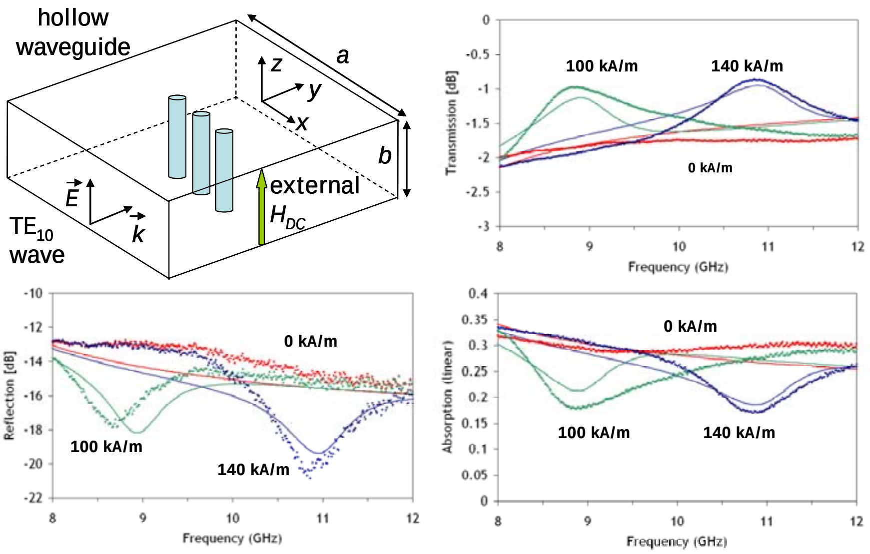

Fig. 1: Schematic of the experimental setup and obtained results for transmission, reflection and absorption (measurements: symbols, simulation: lines).

3. Analysis and discussion

A comparison between measured and simulated results is given in Fig. 1. Data for a 3 wire configuration are displayed in terms of the transmission, reflection and absorption coefficients at different polarization magnetic fields in a WR-90 waveguide (8 to 12 GHz). Sample microwires have in this case a chemical composition of $Fe_{72.5}Si_{12.5}B_{15}$. Figure 1 shows that a relatively good agreement is found between theoretical and experimental results, demonstrating that the theoretical model captures the physics behind this experiment. It is shown that the model approximately predicts the frequency variations related to the application of an external magnetic field. They are basically related to H_0, M_s and γ. Also, maximum values of the transmission and reflection coefficients can be recovered especially if the parameters related to the losses are adjusted.

Finally, the observed decrease of the absorption coefficient corresponding to the transmission window is also predicted by the theoretical model. The decrease of absorption is associated to the fact that the skin depth is comparable to the wire radius (thick wires act as reflectors). Simulations with thicker wires show significantly different behaviours. The transmission window is produced in the region where double negative values of permittivity and permeability co-exist. The wire conductivity locally generates a negative permittivity value, as it happens in general for metals at microwave frequencies. This is a broadband response. However, permeability is negative only in a reduced part of the spectrum, between FMR and FMAR, which roughly corresponds to the 8.2 to 11 GHz band.

Figure 2 shows the e_{rf} and h_{rf} amplitude patterns in the vicinity of the central wire in the 3 wires array when an external magnetic field H_0 = 140 kA/m is applied. The fields are plotted at two frequencies: 10.9 GHz in Fig. 6, and 9 GHz in Fig. 7. The first frequency corresponds to the maximum transmission, as from Fig. 1; and second frequency is almost out of the increased transmission range. The influence of the small wire radius is clearly visible since the EM field fully penetrates inside the wire. The resonance phenomenon is clearly visible in the magnetic field, but it is only slightly observable in the electric field. Skin depth δ is comparable to the wire radius (r = 2 μm). Uniform e_{rf} field values are obtained inside the wire at both frequencies. At 10.9 GHz, the wire section exhibits an important magnetic field variation related to the FMR phenomenon, with extreme values on the wire border. To obtain the enhanced transmission it is very important that the radius of the wires is small (comparable to the skin depth) in order to produce a good interaction between the EM wave and the ferromagnetic core. If this radius is large, the inner part of the wires will not interact with the EM wave and will behave as a simple conductor that produces a reflection of the EM wave.

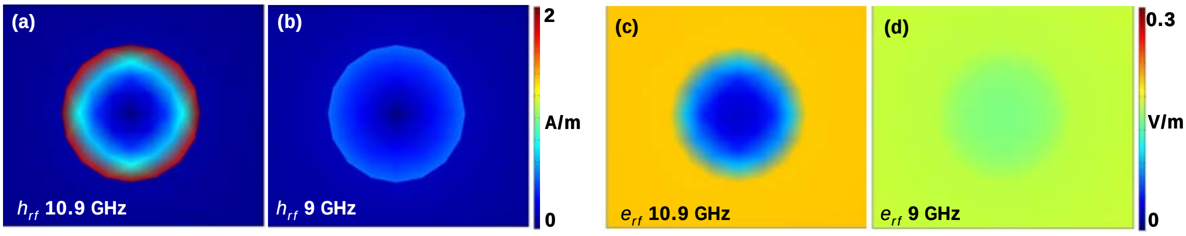

Fig. 2: Magnitude of magnetic (a)-(b) and electric (c)-(d) field plots in the area around the central wire of the array (3 wires with x = 0) at 10.9 GHz and 9 GHz, for an applied magnetic field of H_0 = 140 kA/m and a normalized TE_{10} incident wave of 1 mW of power..

4. Conclusion

In this paper, an experimental and numerical analysis of different configurations of ferromagnetic microwires in a waveguide environment has been presented. Transmission, reflection and absorption coefficients have been measured for different compositions of the microwires and with different applied magnetic fields, covering a wide frequency range. Experimental results have been explained in terms of a theoretical model that captures the underlying physics by properly characterizing a double negative response in terms of effective permittivity and permeability. Small radius and moderate conductivity of the microwires are key elements to obtain the desired effect. It is therefore concluded that a ferromagnetic wire can be considered as the unitary constituent of a double negative medium.

Acknowledgment

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References

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