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Electromagnetic Properties of Composites CoFeNiBSiMo, CoFeBSiCr and CoMnSiB in wide frequency bande

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Abstract. In this paper, our study is based on composites with ferromagnetic wire with a frequency region in the microwave regime with scattering spectra strongly dependent on an external magnetic field and the microwire periodicity. Three types of composites made of grids of continuous and short-cut wires CoFeNiBSiMo, CoFeBSiCr and CoMnSiB are considered to employ different types of spectra of the permittivity and permeability in the frequency band 1 GHz-12 GHz. The complex permittivity increases remarkably with the increase of microwire periodicity, with negative real permittivity is observed over frequency range for wires. With this increase in the microwire periodicity, first we note decreased minimum reflection loss and maximum absorption.

1. Introduction

The knowledge of intrinsic material properties (permittivity and permeability) is required in most digital applications including monolithic microwave circuits using wide frequency range. There are various techniques for extracting these properties; some are single frequency while others offer broadband characterization. Composite structural materials containing periodic or random microwires of conducting scattering elements have received much attention because they make it possible to engineer a selective spectral response to the electromagnetic radiation. It has been demonstrated that composites with conducting wires possess a number of unique properties at microwave and optical frequencies, such as anomalous large photonic band gaps, and resonance like anomalous dispersion of the effective dielectric permittivity also associated with negative values. A recent trend is to achieve the adjustability of these materials [1], [2], [3].

The composite wire with metal incorporated can show a high dispersion of the effective permittivity in the microwave range. By using ferromagnetic wire, it is possible to adjust the sensitivity of this dispersion by changing the size, the magnetic structure of the wire with mechanical or thermal external magnetic stimuli.

2. Mathematical formulation of the proposed method

2.1. Modelling effective permittivity for composite with wire

The microwave tunable properties of a microwire composite are the response of effective permittivity to the electromagnetic wave through the surface impedance. Therefore, to explain this phenomenon, one needs to understand the basics of wave interactions with the materials and the effective medium approaches to characterize heterogeneous composites. The effective permittivity can be treated in two different types of composite [1]:

- Drude model: is applicable to composite materials containing long wire.
- Lorentz model: for composite containers short wire, this model is effective and applicable to all insulation materials.

The effective permittivity is defined [3], [4] :

$$\varepsilon_{eff}=\varepsilon_d+4\pi p<\alpha> \quad (1)$$

α is the polarisability of an individual inclusion and εd is the dielectric permittivity matrix, and $p=\frac{\pi a^2}{b^2}$ is the surface concentration of wire embedded in matrix.

The interaction between the short wire inclusions is neglected; the average polarization of a wire defined in equation (1) is given by [5]:

$$<\alpha>=\frac{1}{2\pi\ln\left(\frac{b}{a}\right)(Ka)^2}\left(\frac{2}{Kb}\tan\left(\frac{Kb}{2}\right)-1\right) \quad (2)$$

With

$$K=\frac{\omega\sqrt{\varepsilon_d}}{c}\left(1+\frac{ic\varsigma_{xx}}{\omega a\ln\left(\frac{b}{a}\right)}\right)^{1/2} \quad (3)$$

For continuous composite wire, the effective permittivity also depends on the wire surface impedance. In this case, there are no charge distribution along the wire and associated dipole resonances. As a result, the effective permittivity for waves with the electric field polarization along the wires has a characteristic plasma dispersion behavior [5]. The effective permittivity:

$$\varepsilon_{eff}=\varepsilon_d-\left(\frac{\omega_p}{\omega}\right)^2 \quad (4)$$

With ω_p the plasma frequency:

$$\omega_p^2=\frac{2\pi c^2}{b^2\ln\left(\frac{b}{a}\right)} \quad (5)$$

In the case of a strong skin effect and due to the Giant magneto-impedance effect GMI, It is possible to write the solution of the electric field in the system which depends on the wire conducting and magnetic properties through the surface impedance. The effective permittivity of a plasma dispersion behavior is given by:

$$\varepsilon_{eff}=\varepsilon_d-\frac{p\omega_p^2}{\omega^2\left(1+i\frac{c\varsigma_{xx}}{\omega a\ln\left(\frac{a}{b}\right)}\right)} \quad (6)$$

In the case of a strong skin effect in the inclusions and a scalar permeability μ, the surface impedance is determined by the Leontovich condition [6].

$$\varsigma_{xx}=(1-i)\sqrt{\frac{\omega\mu}{8\pi\sigma}} \quad (7)$$

Following the low-field GMI phenomena utilized for field sensing, this section is focused on the high field absorption that can be potentially used for stress sensing. Here we treated theoretically the GMI phenomenon in the microwave frequency range by analyzing the ferromagnetic resonance (FMR), which is considered to be related to the high-frequency GMI. Using the classic Landau– Lifschitz–Gilbert equation [7], in the case of ferromagnetic wires or composite containing arrays of wires, one can obtain equation (8) to calculate the variation of the complex component of permeability with varying applied magnetic fields. [8].

$$\mu=1+\frac{\mu_0\gamma M_s[\mu_0\gamma(H_{dc}+H_k)-i\omega\alpha]}{-\omega^2+\omega_{fmr}^2-i\omega\alpha\mu_0\gamma[2(H_{dc}+H_k)+M_s]} \quad (8)$$

Where μ_0 is the vacuum permeability, α is the damping parameter, γ is the gyromagnetic parameter, M_s is the saturation magnetization, H_{dc} denotes the applied magnetic field, H_k is the anisotropy field and ω_{fmr} denotes the angular resonance frequency which is given by:

$$\omega_{fmr}=\mu_0\gamma\sqrt{(H_{dc}+H_k+M_s)(H_{dc}+H_k)} \quad (9)$$

It is reasonable to infer that, in addition to the magnetic field, stresses also produce a similar effect by modifying the magnetoelastic anisotropy of the microwires as expressed in equation:

$$H_k=\frac{3|\lambda_s|}{M_s}(\sigma_{zz}-\sigma_{\varphi\varphi}+\sigma_{app}) \quad (10)$$

Where λs is the magnetostriction constant, σ_{zz}, $\sigma_{\varphi\varphi}$ and σ_{app} are the longitudinal internal stress, radial internal stress, and applied stress, respectively [1], [8].

2.2. Microwave absorption

Absorption is a phenomenon that occurs when microwaves interact with the materials. The absorption or attenuation originates from the dielectric loss and the magnetic loss. For a single layer composite, reflection loss RL [9] is given by:

$$RL=20\log\left|\frac{\sqrt{\frac{\mu}{\varepsilon}}\tanh\left(i\frac{\omega d}{c}\sqrt{\mu\varepsilon}\right)-1}{\sqrt{\frac{\mu}{\varepsilon}}\tanh\left(i\frac{\omega d}{c}\sqrt{\mu\varepsilon}\right)+1}\right| \quad (11)$$

With d is thickness of the absorber. The attenuation constant α is the real part of the propagation constant, given by:

$$\alpha=\mathrm{Re}\left(\frac{i\omega\sqrt{\mu\varepsilon}}{c}\right) \quad (12)$$

ε and μ are the relative permittivity and permeability of the absorbing material, respectively. For a magnetic absorber, the matching frequency can be regarded as the ferromagnetic resonance frequency, which can be given as:

$$\omega=\gamma H_k \quad (13)$$

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3. Results and discussions

The microwave properties of wire composites were investigated for different types of samples wire glass coated amorphous CoFeNiBSiMo, CoFeBSiCr and CoMnSiB with radius of a=5 µm were glued in paper to form wire-lattices with separation b. Calculations are performed in the frequency range of 1GHz-12GHz. The flowchart of calculating the complex effective permittivity and effective permeability are given by proposed algorithm:

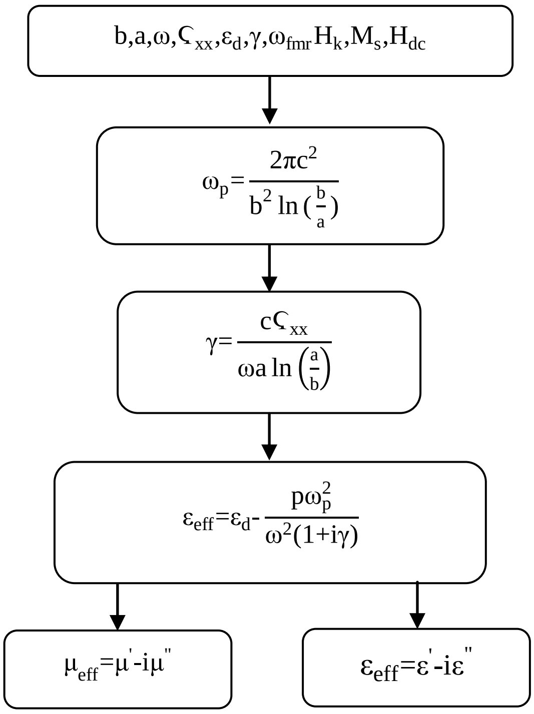

Table1. Material parameters obtained from tests magnetization

Composite wire	Wire radius a (µm)	Anisotropy field H_k (A/m)	Gyromagnetic ratio γ ($mA^{-1}.s^{-1}$)	Saturation magnetization $4\pi M_s$ (A/m)	Damping parameter α	Conductivity σ (s/m)
CoFeNiBSiMo	5	880	$2, 21x\ 10^5$	10^6	0.02	10^{16}
CoFeBSiCr	5	500	$3,76x10^4$	5.10^5	0.01	$7,7x\ 10^5$
CoMnSiB	5	880	$2,51x10^5$	5.10^5	0.02	$7,6x10^{15}$

3.1. The effective permittivity

Figures (1), (2) and (3) illustrate the variation of the effective complex permittivity of the frequency as a function of the periodicity thickness for composite wire in a magnetic field. The material parameters obtained from tests magnetization are given in table 1.

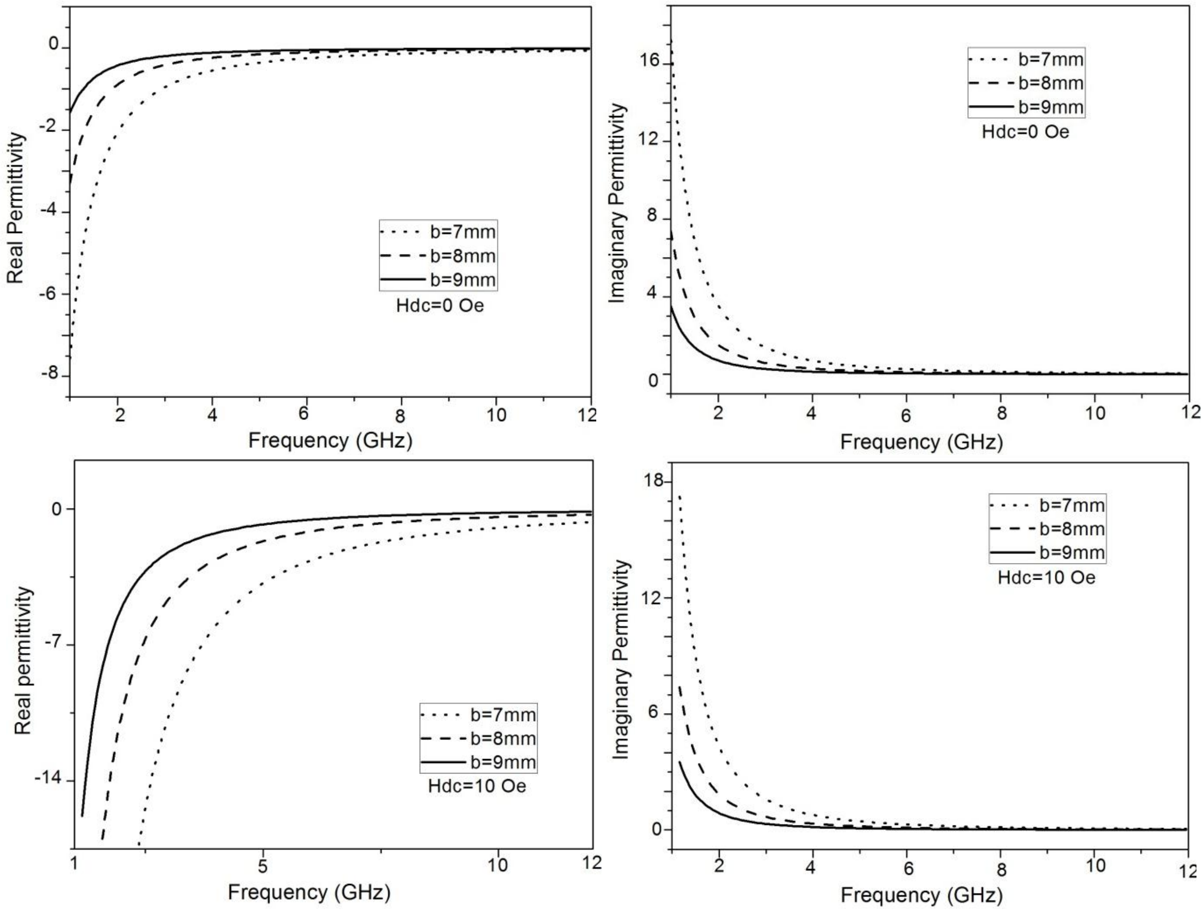

Figure1. Variations of the real part and the imaginary part of the effective dielectric permittivity depending on the frequency for CoFeNiBSiMo

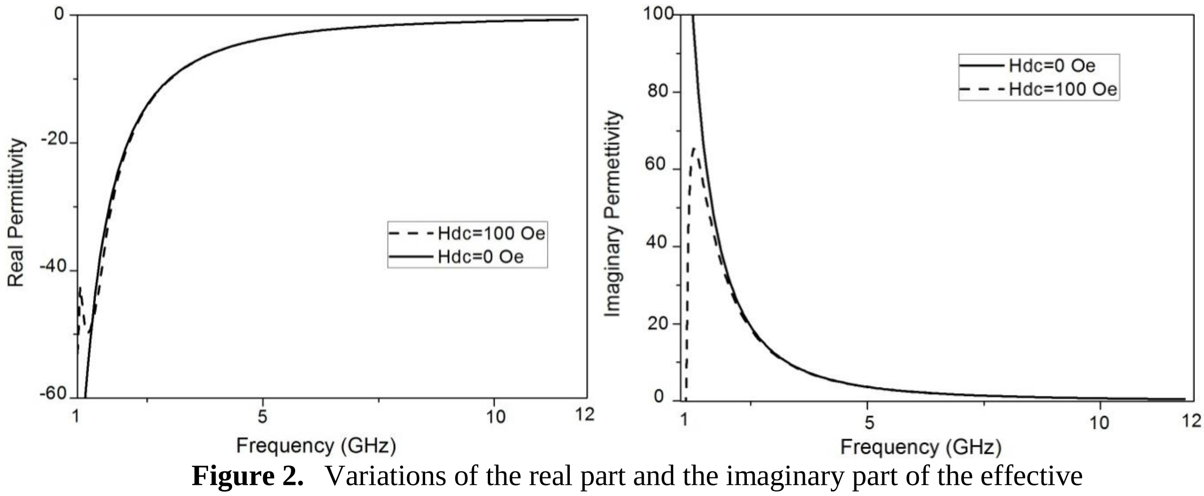

Figure 2. Variations of the real part and the imaginary part of the effective dielectric permittivity depending on the frequency for CoMnSiB

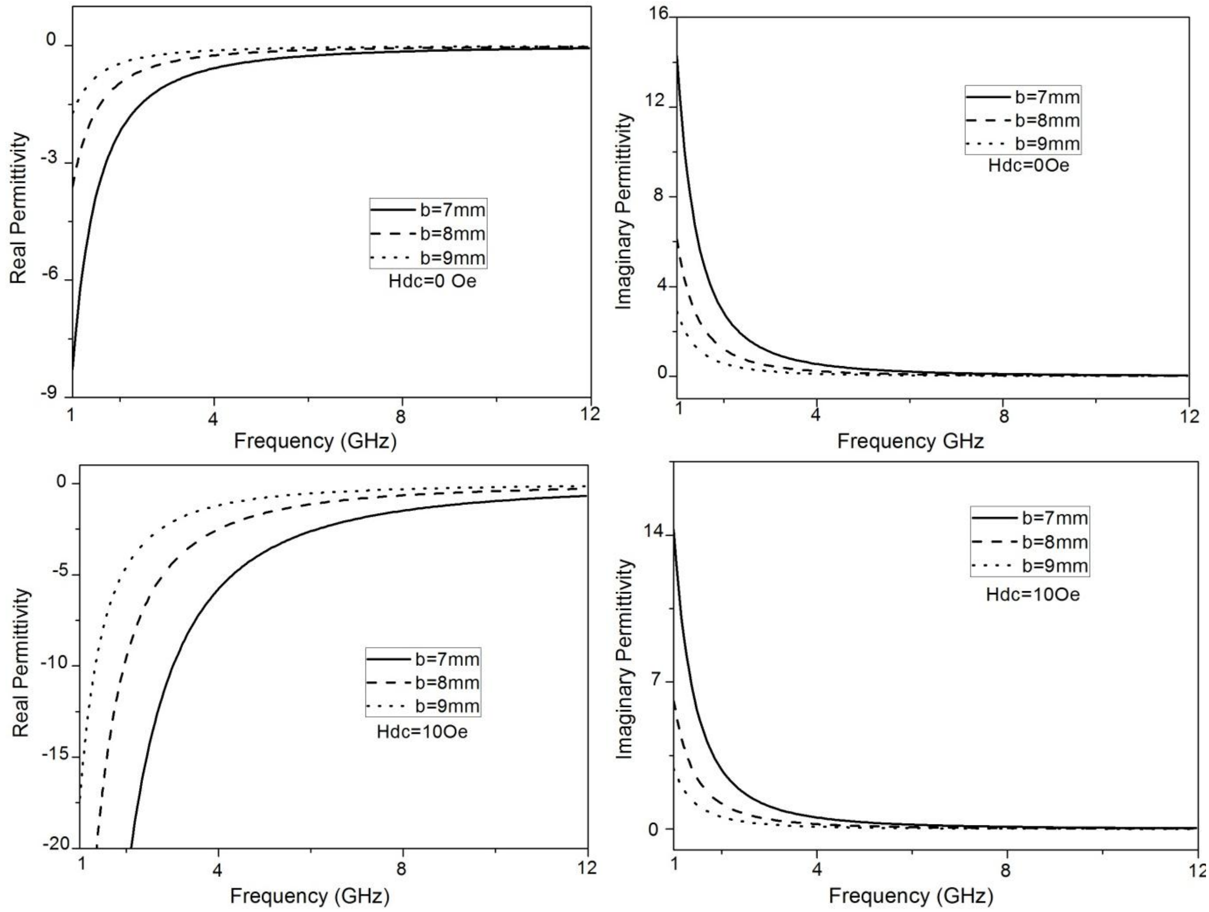

Figure3. Variations of the real part and the imaginary part of the effective dielectric permittivity depending on the frequency for CoFeCrSiB

The spectra (1), (2) and (3) show, respectively, the variation of the effective complex permittivity in a frequency band 1GHz-12 GHz, depending on the periodicity of wires, with the excitation of an external magnetic field for three different composites, CoFeNiBSiMo, CoMnSiB and CoFeCrSiB. First, it is clear that the effective permittivity depends on both the excitation and the periodicity of the composite through the frequency band 1GHz-12GHz. On the other hand, the plasma frequency is a function of the periodicity of the test composite. It can also be seen that, with the increasing wire periodicity from 7mm to 9 mm, the frequency dispersion of effective permittivity on the magnetic field is remarkably a damped manner. However, a decrease of wire periodicity will increase the plasma frequency and hence the skin effect. If the skin effect is too strong, the field effect will be rather weak. Therefore, the wire diameter may also need to be decreased to compensate the decrease of skin depth. Thereby, there exists an optimum value of wire periodicity matching the diameter for the microwave tunable properties.

3.2. The effective permeability

According to the Landau–Lifshitz–Gilbert equation (8), the permeability is strongly dependent on the anisotropy field of the wires. Considering the significant stress impact on the anisotropy field of wires [1], [5] and anisotropy angle, the permeability (or impedance) spectra can be regulated by the variation of internal stress due to that of geometry or glass-removal; and external stress [8] as shown in equation (10). The resonance frequency can be regulated by the parameter of the microwires and thickness of the absorber (number of wires).

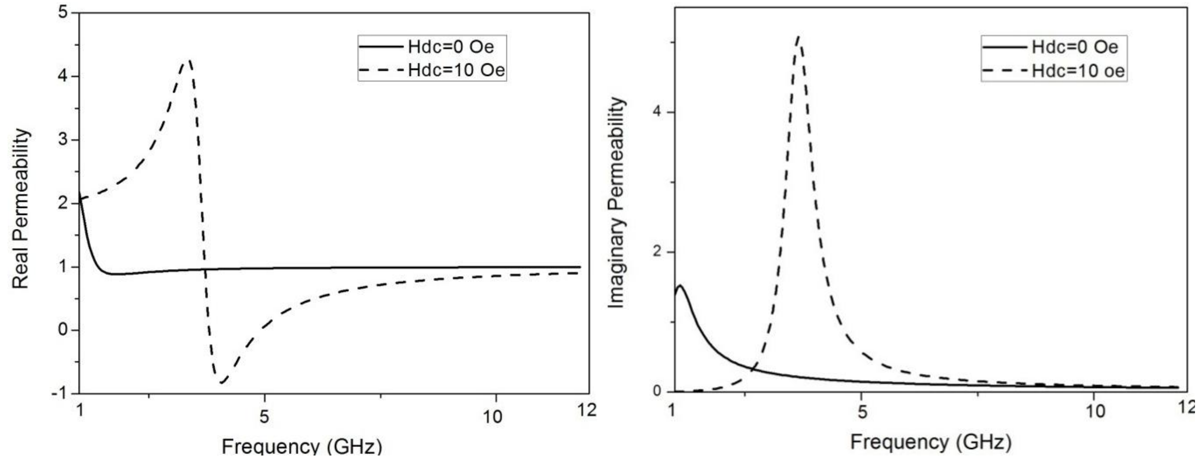

Figure4. The spectra of the real and imaginary part of the effective permeability for CoFeNiBSiMo

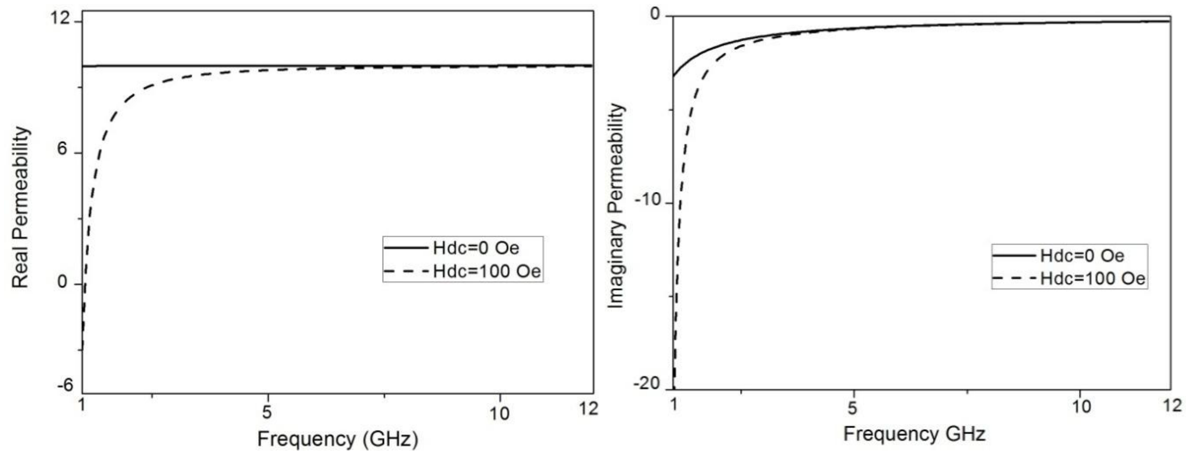

Figure5. The spectra of the real and imaginary part of the effective permeability for CoMnSiB

3.3. The reflection loss

The field dependence of the effective permittivity of the composite is caused by the field dependence of the surface impedance matrix ς_{xx}, which determines the losses inside the inclusions. The figure (6) show respectively, the typical relationship between reflection loss, absorption and measuring frequency of the composites containing the wires CoFeNiBSiMo, with the thickness of absorber d=2,1mm. It shows the frequency dependence of the reflection loss taken at a magnetic field for the composite with b = 7 mm, and 9 mm. It can be seen that the shape of the curves varies remarkably as the wire periodicity increases from 3 mm to 9 mm. The increase of microwire periodicity, the minimum reflection loss decreases firstly and then increases, and shifts towards lower frequency region. It is seen that the plots for Hdc=10 Oe circumferential magnetization have a resonance behavior with a resonance frequency of 3,75GHz, an absorption peak, and a negative real part of the permittivity in a wide frequency band past the resonance. In the presence of the magnetic field larger than the anisotropy field which saturates the magnetization along the axis and increases the wire surface impedance, the dispersion of effective permittivity becomes a relaxation type with a gradual decrease in the imaginary part, which is always positive and with very broad losses [2].

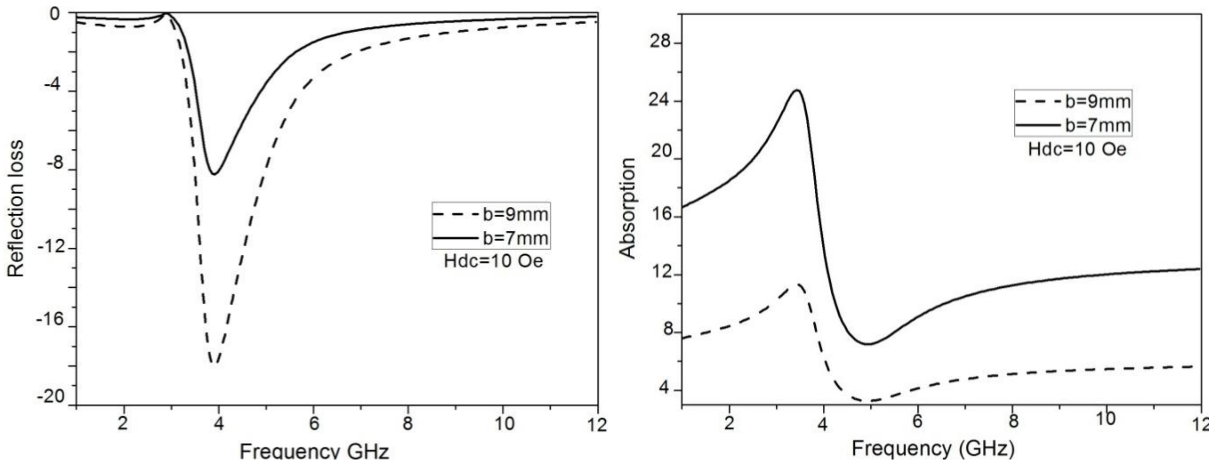

Figure6. The spectra of reflection loss and absorption as a function of frequency for CoFeNiBSiMo

4. Conclusions

In This document, the effects from the parameters of the wire on the dielectric and magnetic response depend on the nature of the ferromagnetic microwires composite, continuous in the frequency range from 1 GHz to 12 GHz, using a calculation of the effective permittivity according to the impedance of the wire surface. The real and imaginary parts of the effective permittivity show great variations with the frequencies and the wire parameters, also in the domain due to the field dependency of the impedance of the wire that controls the losses in the dielectric response. Thus, the composite wire has a Plasmon dispersion of the effective permittivity with negative values of its real part lower than the plasma frequency is in the gigahertz range for the wire spacing of about 1 cm and a diameter wire a few microns.

References

[1] F.X. Qin., and H.X. Peng, 1995 *Ferromagnetic microwires enabled multifunctional composite materials*". Progress in Materials Science 58, pp. 183–259, 2013

[2] S.I. Bozhevolnyi., I.I. Smolyaninov and A.V. Zayats,. *Near-field microscopy of surface-plasmon polaritons: Localization and internal interface imaging*, Physical. Review B 51, pp.17916-17924.

[3] A. N. Lagarkov, and A. K. Sarychev, 1996 *Electromagnetic properties of composites containing elongated conducting inclusions*, Physical Review B 53, 6318.

[4] A.N. Lagarkov, S.M. Matytsin, K.N. Rozanov and A.K. Sarychev, 1998 *Dielectric properties of fiber-filled composites*, Journal of Applied Physics 84, pp. 3806–3814.

[5] L.V. Panina, S.I. Sandacci and D.P. Makhnovskiy, 2005 *Stress effect on magnetoimpedance in amorphous wires at gigahertz frequencies and application to stress-tunable microwave composite materials*, Journal of Applied Physics 97:013701–6.

[6] Makhnovskiy D.P., L.V. Panina, C. Garcia, A.P. Zhukov and J. Gonzalez, 2006 *Experimental demonstration of tunable scattering spectra at microwave frequencies in composite media containing CoFeCrSiB glass-coated amorphous ferromagnetic wires and comparison with theory*, Physical Review B 74, 064205.

[7] L.D. Landau and E.M. Lifshitz, 1975 *Electrodynamics of continuous Media, In: Course of*

theoretical physics – Pergamon international library of science, technology, engineering and social studies. Oxford: Pergamon Press.

[8] F.X. Qin, H.X. J. Peng, and L.C. Qin, 2010 *Ferromagnetic microwires enabled polymer composites for sensing applications*, Compos Part A: Applied Science and Manufacturing 41, pp. 1823–1828.

[9] Z. Zhang, C. Wang, Y. Zhang and J. Xie, 2010 *Microwave absorbing properties of composites filled with glass-coated Fe69Co10Si8B13 amorphous microwire*, Materials Science and Engineering B 175, pp. 233–237.