Magneto-Impedance and Ferro-Magnetic Resonance effects in thin amorphous wires and their application in functional composites materials at microwaves

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Abstract **– The effect of the external magnetic field on microwave response from composites containing CoFeSiBCr amorphous wires has been demonstrated by measuring S-parameters in free space in the frequency band of 0.9-17 GHz. Two types of composites made of lattices of continuous and short –cut wires are considered to employ different types of spectra of the dielectric function (plasmonic and resonant). In both cases, the application of the field increases the dielectric losses owing to increase in the wire impedance. The observed changes in the reflection/transmission spectra are more than 10% in a certain lower frequency range. The results are analyzed in terms of the effective permittivity.**

1 INTRODUCTION

Composites with embedded metallic wires may demonstrate a strong dispersion of the effective permittivity εef in the microwave range [1-4]. The use of ferromagnetic wires makes it possible to sensitively tune this dispersion by changing the magnetic structure of the wire with external magnetic, mechanical or thermal stimuli. The possibility to control or monitor the electromagnetic parameters (and therefore scattering and absorption) of composite metamaterials is of great interest for large-scale applications such as remote non-destructive testing, structural health monitoring, tuneable coatings and absorbers. The magnetic tunability of microwave response was reported in a number of works for different types of wire media demonstrating that underlying physics is related with the magnetoimpedance (MI) effect in wires [5-7]. In this work, we consider two types of magnetic wire composites (see Fig.1): arrays of continuous wires and of short-cut wires made of CoFeSiBCr glass coated amorphous wires showing large MI [8]. We demonstrate that in the both cases the application of a magnetic field to the whole composite strongly increases the dielectric losses, which affects the reflection/transmission spectra.

2 EFFECTIVE PERMITTIVITY OF WIRE MEDIA

Composites containing long parallel wires as shown in Fig.1a may support very low frequency plasmons and can be characterised by plasma-like dispersion of ε_{ef} [1-2] with a negative value of the real part of the permittivity below the characteristic plasma frequency, f_p:

$$\varepsilon_{ef}^2 = 1 - \frac{\omega_p^2}{\omega^2 (1 + i\gamma)}, \quad \omega_p = 2\pi f_p,$$

$$f_P^2 = \frac{c^2}{2\pi b^2 \ln(b/a)} \qquad (1)$$

Here, γ is the relaxation parameter and c is the velocity of light. For wire radius a in the micron range and spacing b between them of about 1cm the

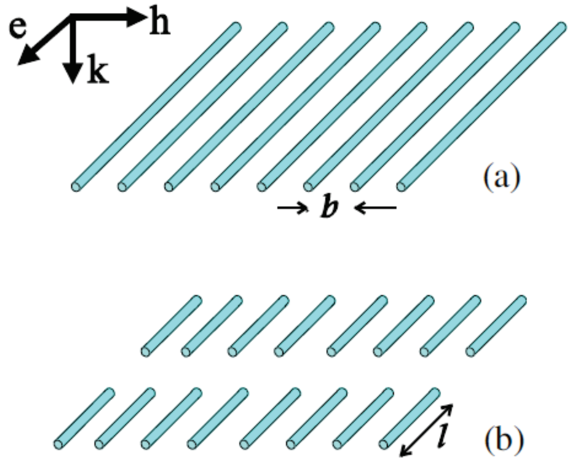

Figure 1: Sketch of the wire composites

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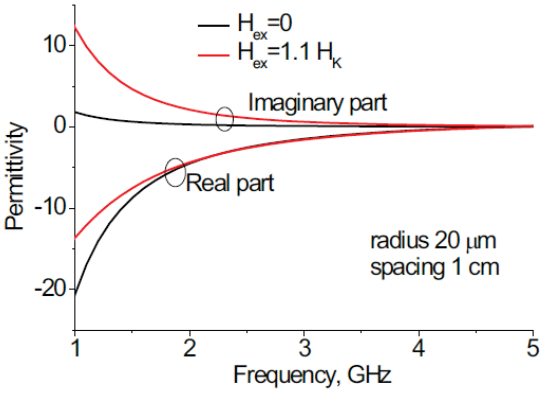
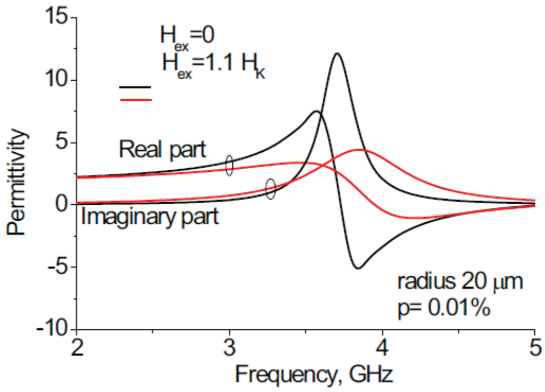
characteristic plasma frequency is about 4 GHz. A



(a)



(b)

Figure 2 1Effective permittivity spectra in composites depicted in Figs. 1(a), (b), respectively,

number of experimental studies confirmed a negative permittivity in the GHz region for wire media. In some works, the relaxation is ignored which could be justified in the case of a very strong skin effect. We have demonstrated that in general γ is defined by the wire surface impedance ς_{zz} :

$$\gamma = \frac{c\varsigma_{zz}}{\omega a \ln(b/a)} \qquad (2)$$

For magnetic wires, this parameter may change greatly when an external magnetic field is applied as a result of the MI effect. Then, the permittivity spectra will depend on the external magnetic field as demonstrated in Fig. 2a.

The composites with short-cut wire inclusions as shown in Fig. 1b are characterized by a resonance type

of the ε_{ef} as the wires behave as dipole antennas with the resonance at half wave length condition: $f_R = c/2l\sqrt{\varepsilon_d}$, where ε_d is the permittivity of the supporting matrix. If the interaction between the wires is neglected, the effective permittivity is composed of the averaged dipole polarization χ and may be expressed analytically for an important case of not very strong skin effect [7]:

$$\varepsilon_{eff} = \varepsilon + 4\pi p\chi ,$$

$$\chi = \frac{1}{2\pi \ln(l/a)(\tilde{k}a)^2}\left(\frac{2}{\tilde{k}l}\tan(\tilde{k}l/2) - 1\right), \ (3)$$

$$\tilde{k} = k\left(1 + \frac{ic\varsigma_{zz}}{\omega a \ln(l/a)}\right)^{1/2}, \ k = \omega\sqrt{\varepsilon}/c \ (4)$$

Here p is the wire volume concentration and, $\tilde{k}$ is the renormalized wave number. Comparing equations (2) and (4) it is seen, that in both cases the dependence on the wire surface impedance occurs in a similar way, controlling the dielectric losses in the case of a moderate skin effect. The permittivity spectra for short-cut wire composites are given in Fig. 2b. It is seen that applying a magnetic field which increases the wire impedance suppresses the resonance behavior due to increased losses

Amorphous ferromagnetic microwires with negative magnetostriction having a circumferential anisotropy are characterized by large change in impedance when subjected to an axial magnetic field which rotates the magnetisation away from the circular direction. This effect remains essential even at GHz frequencies. This makes them very promising for engineering artificial dielectrics with tuneable microwave properties. As the wire impedance depends on the dc magnetisation (via the ac permeability) it is expected that any physical effect (magnetic field, mechanical stress, temperature) that results in change in the magnetic structure (whilst the ac permeability remains high) will affect the dispersion of the effective permittivity.

3 EXPERIMENTAL

The microwave properties of wire composites were investigated by free space methods requiring large samples. Co_{66} $Fe_{3.5}B_{16}Si_{11}Cr_{3.5}$ glass coated amorphous wires with radius of 20 μm were glued in paper to form wire-lattices of 50x50 cm^2 with separation b of 10 mm, as shown in Fig. 1a. After measurements, such wire-lattice was sequentially cut in stripes of 40, 20 and 10 mm wide to form the composites with short dipole wires as depicted in Fig. 1b. The S-parameters were measured in the frequency range of 0.9-17 GHz in the presence of external field

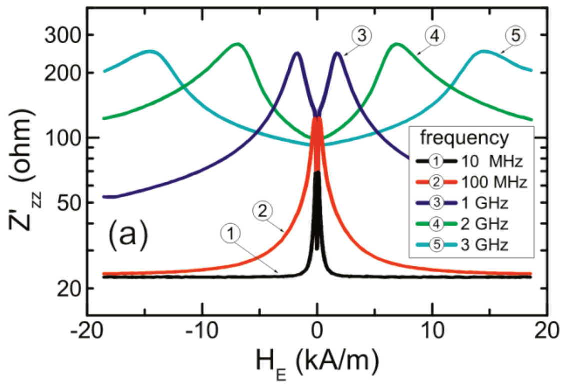


Figure 3: Wire impedance vs. field for different frequencies.

ranging up to 3000A/m applied through a plane coil with turns perpendicular to the electrical field in the incident wave. The effective permittivity spectra were deduced from S-parameters with the help of Reflection/Transmission Epsilon Fast Model. The magnetic properties of wires were defined from measurements of dc magnetisation loops and MI in the frequency range up to 500MHz.

4 RESULTS AND DISCUSSION

The results on dc magnetisation loops (not shown here) have confirmed that the wires possess a circumferential anisotropy with the effective anisotropy field of about 400A/m. The impedance plots vs. field seen in Fig. 3 have two symmetrical peaks which is typical of circumferential anisotropy and indicate the impedance change ratio up to 300% at 500 MHz

Figure 4 shows the spectra of the reflection R, transmission T, and the effective permittivity ε_{ef} for long-wire composites with the field H_{ex} as a parameter. The relative change in R and T is about 10% at lower frequencies while the phase of transmission shifts about 40 degrees at 1 GHz with the change of the field. The permittivity spectra deduced from R and T plots are consistent with the theoretical plots seen in Fig. 2a. The effective thickness was taken equal to the lattice period of 1 cm. The imaginary part of the permittivity increases with the field due to the increase in the wire impedance resulting in decrease in the transmission amplitude (although the reflection amplitude also decreases).

Figure 5 shows the spectra for cut-wire composites with different wire length of 40, 20 and 10 mm and with the field as a parameter. The transmission spectra have a deep minimum near a resonance demonstrating a stop filter behaviour. The magnitude of this minimum depends strongly on the field for longer wires with lower resonance frequency. For shorter wires with the dispersion at a higher frequency band the field dependence is not noticeable since the wire ac permeability is nearly unity and the impedance becomes insensitive to the magnetic properties. The resonance frequency corresponds to that for wires in the medium with the permittivity of unity. For comparison of two composites, the effective thickness to calculate the effective permittivity was taken 1 cm, however, this may be questionable since even a thin layer of the supporting matrix may change the resonance frequency.

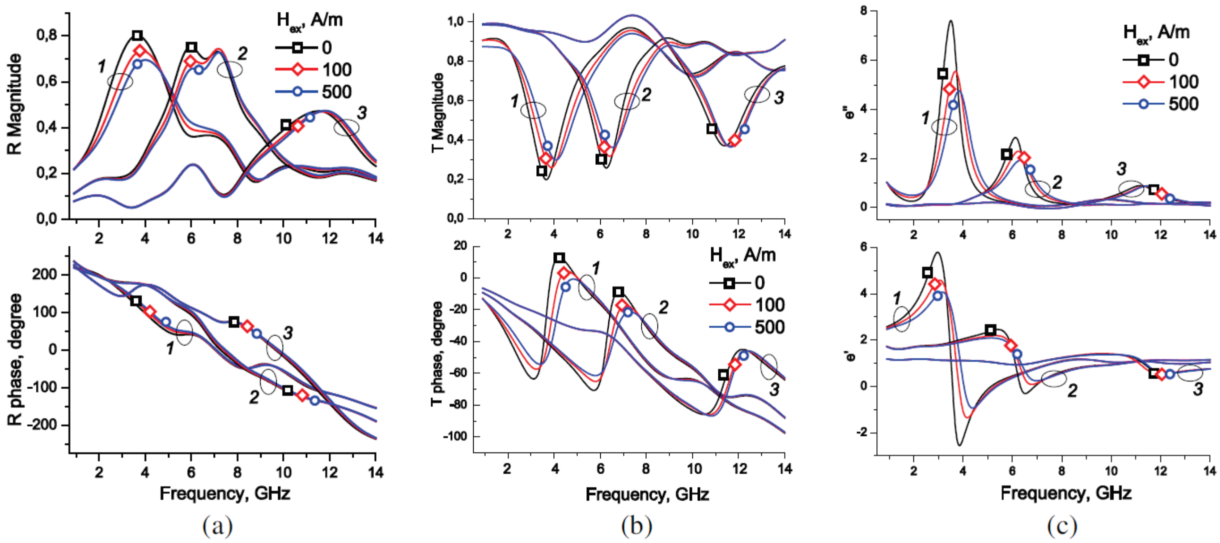
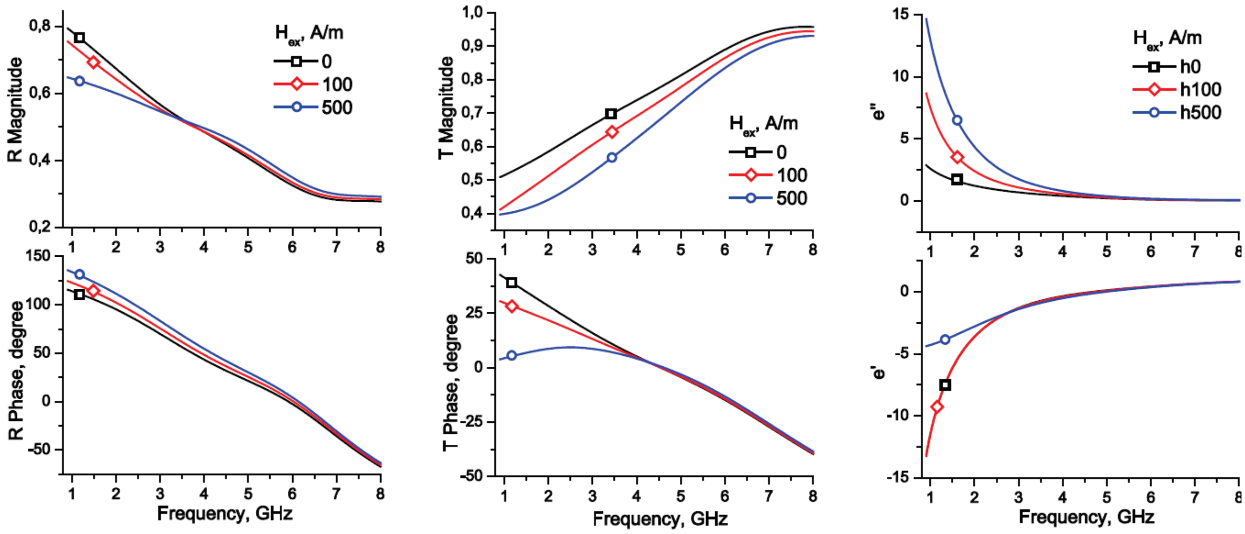


Figure 4: Spectra of R, T and ε_{ef} for composites with long wires with H_{ex} as a parameter



(a) (b) (c)

Figure 5: Spectra of R, T and ε_{ef} of composites with cut wires of length 40 (1), 20 (2) and 10 (3)mm

The phase of the transmitted wave shows a reversal near a resonance frequency which sensitively shifts with the field.

5 CONCLUSIONS

Here we report novel results on the magnetic field effect on the dielectric response in composites with arrays of parallel magnetic wires, continuous and short-cut, in the frequency region of 0.9-17 GHz utilising free-space measurement method and analysis in terms of the effective permittivity depending on the wire surface impedance. Both the real and imaginary parts of ε_{ef} show strong variations with increasing the field owing to the field dependence of the wire impedance which controls the losses in the dielectric response. Long-wire composite has a plasmonic type dispersion of ε_{ef} with negative values of its real part below the plasma frequency which is in the GHz range for wire spacing of about 1 cm and wire diameter of few microns. The presence of the external magnetic field suppresses low-frequency plasmons increasing the value of the real part of the permittivity. In the case of cut-wire composites, it is confirmed that their effective permittivity has a resonance type dispersion due to the dipole resonance in wires at half wavelength condition. The application of the field broadens the resonance and shifts it towards the higher frequencies. Therefore, both types of wire composites possess a strong dependence of the effective permittivity on the external magnetic field and are suitable for large scale applications as tuneable microwave materials.

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